Recent R&D Results from the First Dual Phase Xenon Doped Argon TPC

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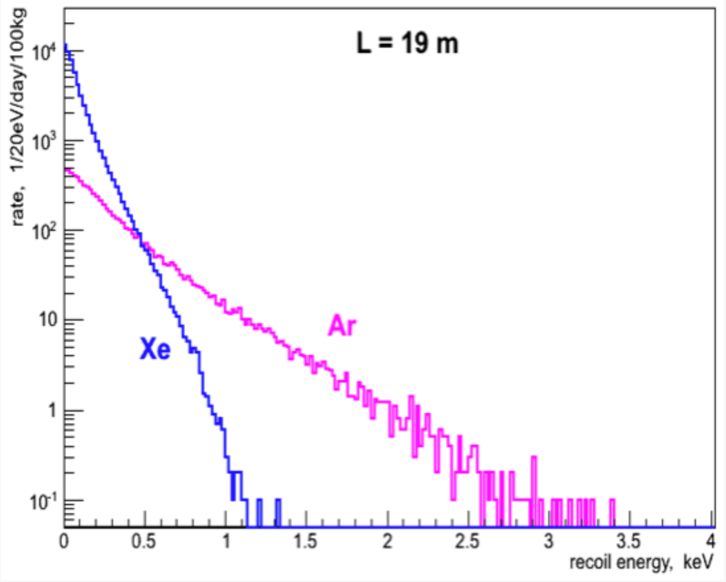
Lawrence Livermore National Laboratory

Applications of Xenon-Doped Argon

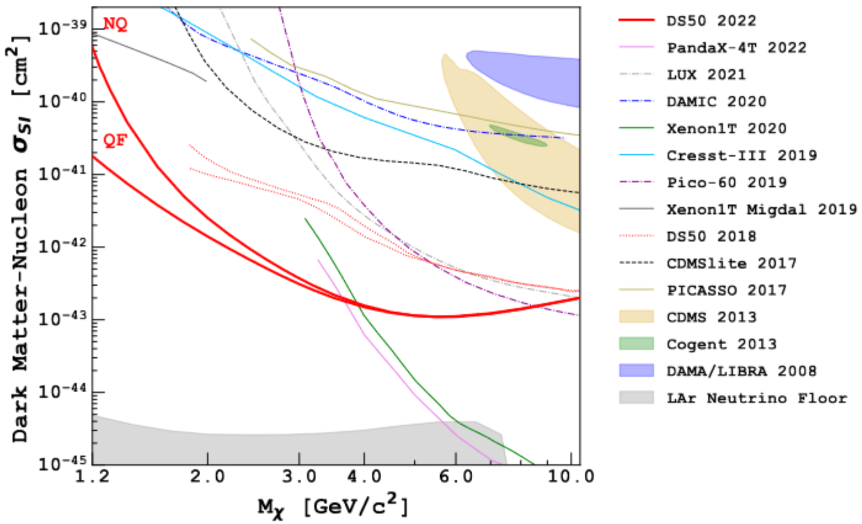
Low energy nuclear recoils:

- Reactor monitoring via CEvNS, sub-GeV dark matter
- Tradeoff: counts vs recoil energy
- Xe: large cross section, low energy recoils
- Ar: smaller cross section, higher (but still low) energy recoils



Argon vs Xenon expected CEVNS rate 19 m from the 3 GW Kalanin Nuclear Power Plant core (RED-100, https://www.mdpi.com/2624-8174/5/2/34)

Darkside 50 Ionization-only limits (https://arxiv.org/pdf/2207.11966)



Review of Xenon and Argon Time Projection Chambers (TPCs)

An energetic particle will generate:

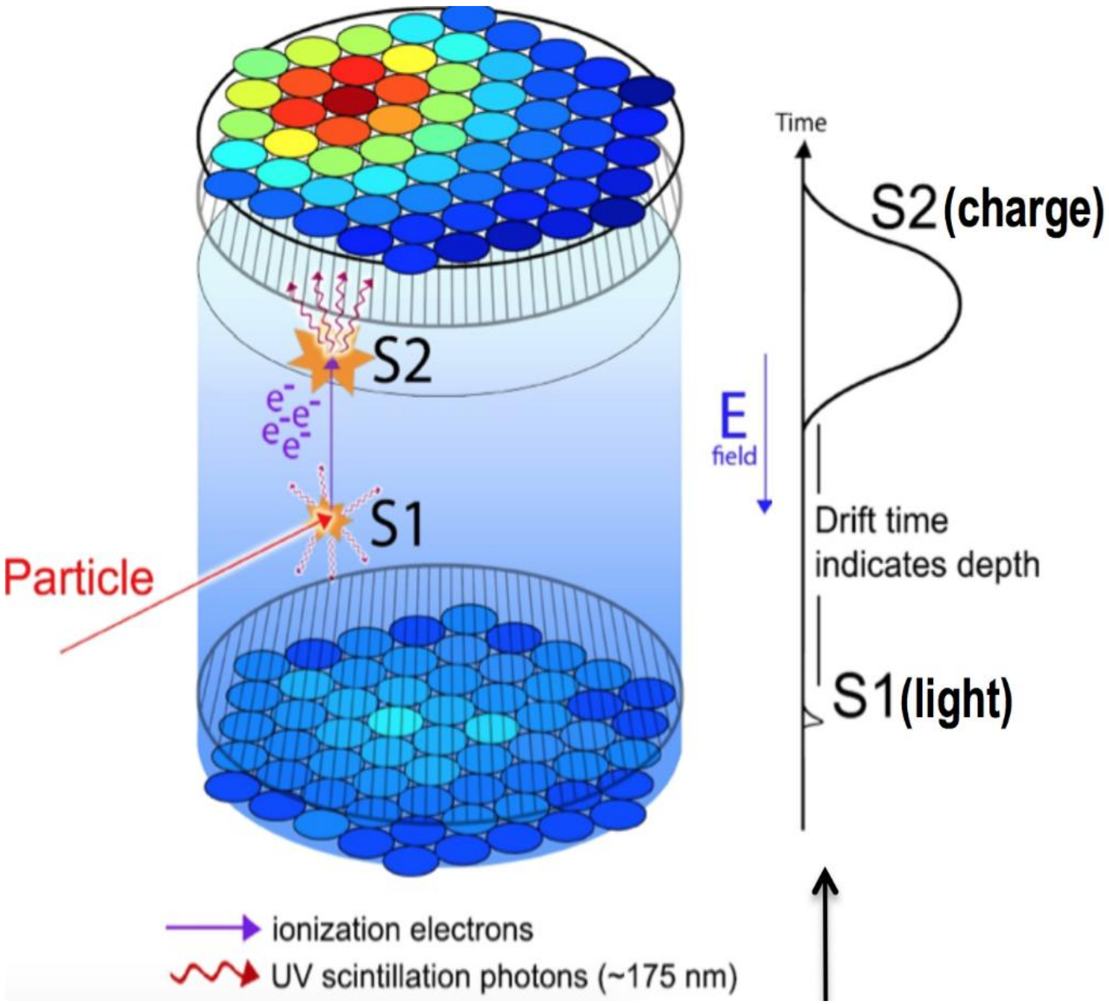
- Scintillation light (S1)
- Ionization electrons (S2)

Photosensors detect S1, electric field drifts electrons

S1 and S2 can tell you:

- Amount of energy deposited
- Particle ID
- 3D Position Reconstruction

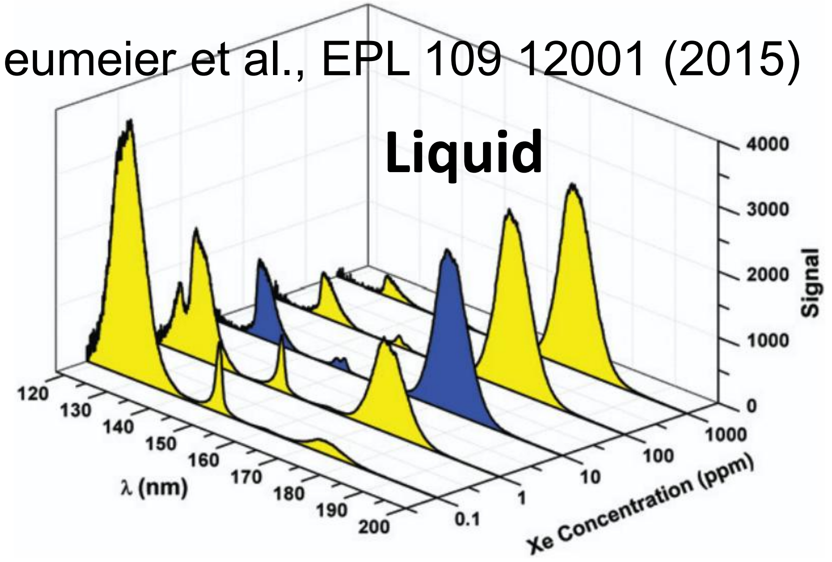
Dual phase is **scalable** and can see **single electrons**



Comparison of (Liquid) Xenon and Argon

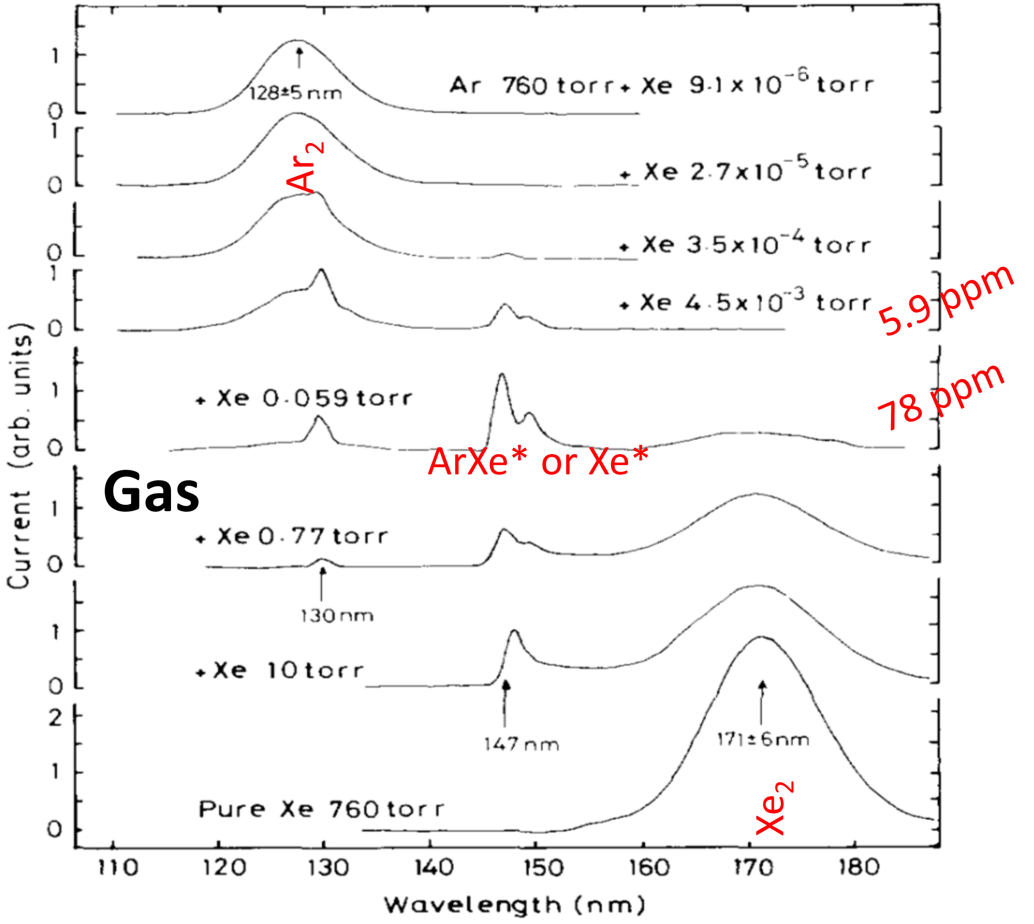
Property	Argon	Xenon
Scintillation wavelength	128 nm	175 nm
Kinetic Match to Light Particles	A = 39.95	A = 131.29
Operation Temperature	~90 K	~160 K
Liquid phase ionization energy	14.3 eV	9.3 eV
Excitation Energy	11.6 eV	8.3 eV
Scintillation lifetime	1.5 us (triplet component)	22 ns
Electron Background	Lower	Higher
Electron Extraction Efficiency	Higher	Lower

Xenon-Doping in Argon



Mixing Xe into Ar shifts 128 nm to 147 nm and 175 nm light!

- Can sharpen pulse shapes (both S1 and S2)
- Longer wavelengths are easier to detect and reflect
- No need for TPB



Emission spectra of xenon-doped argon gas mixtures at 1 atm in a gas proportional counter (T. Takahashi et al. NIM **205** 591-596 (1983))

CHILLAX: CoHerent Ionization Limit of Liquid Argon and Xenon

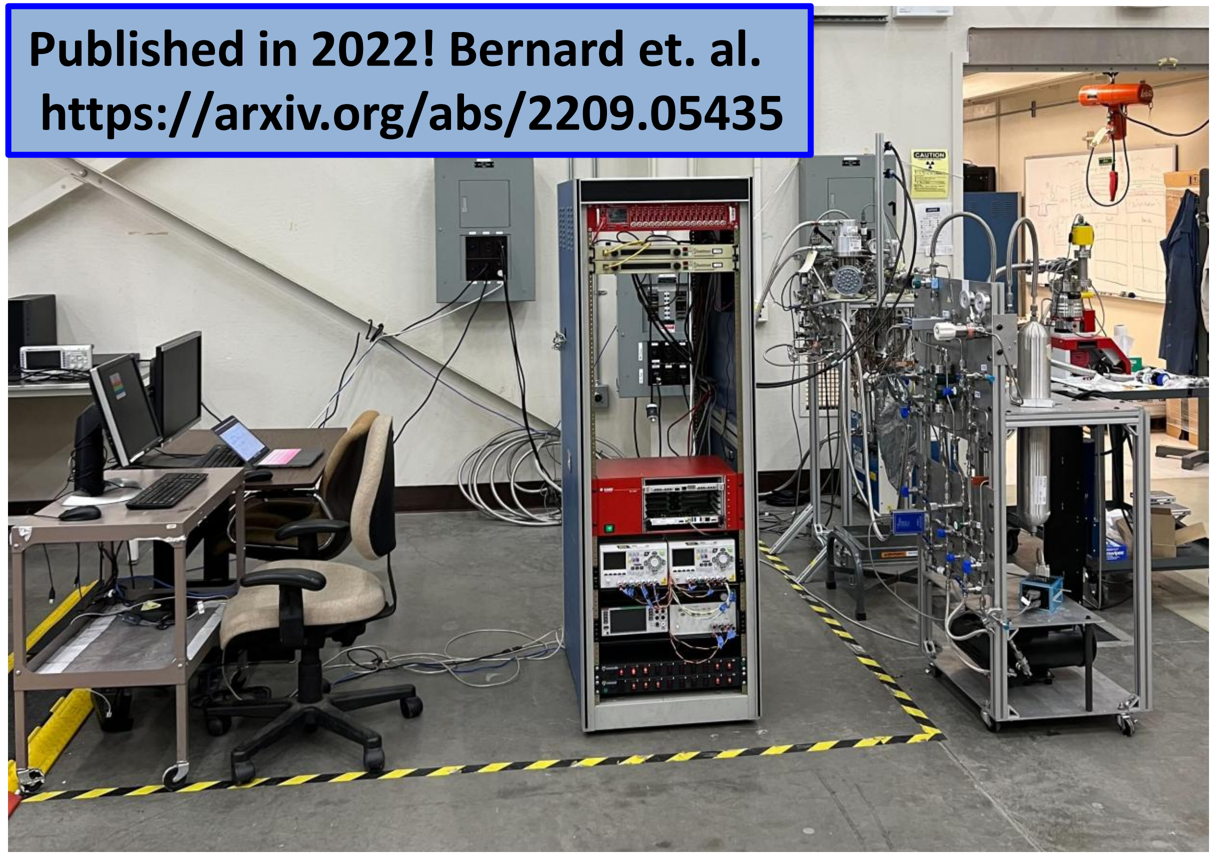
Concept: A liter-scale dual phase xenon-doped argon TPC

<u>Goals:</u>

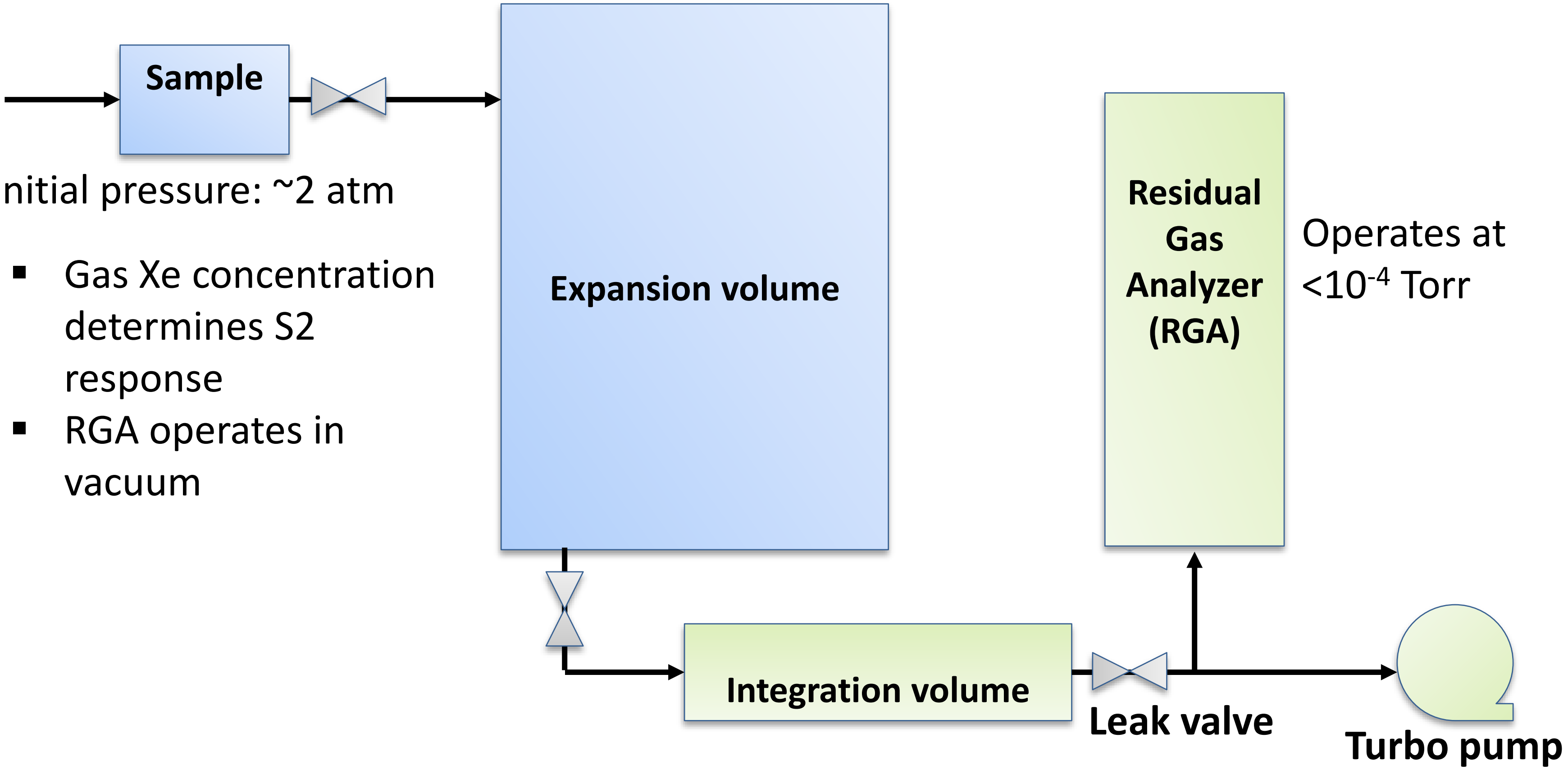
Obtain a stable mixture of percent level Xe in LAr

Quantify potential benefits to dual phase argon TPC's ionization signal from xenon doping

Published in 2022! Bernard et. al.
https://arxiv.org/abs/2209.05435



Gas Sampling



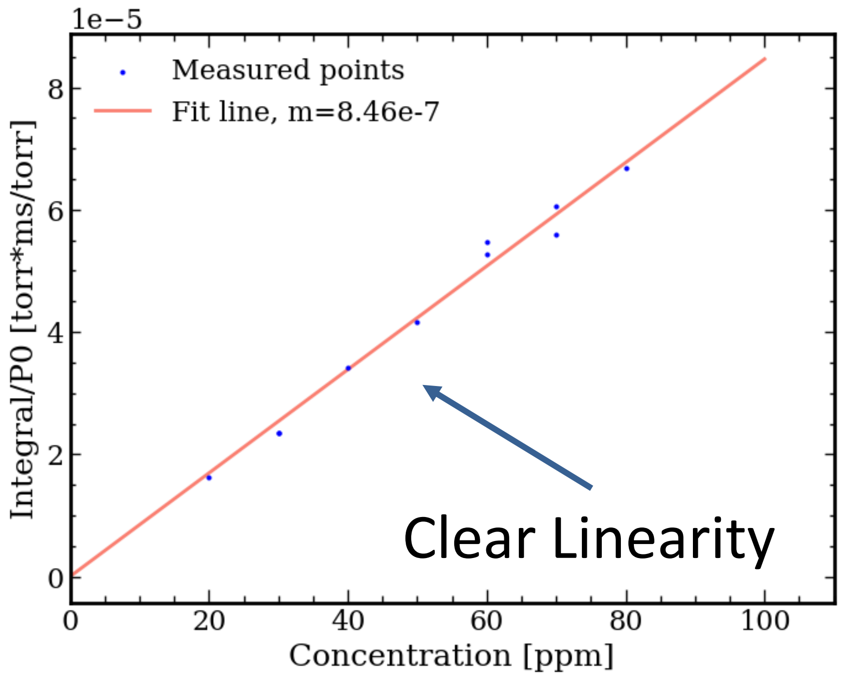
Initial pressure: ~2 atm

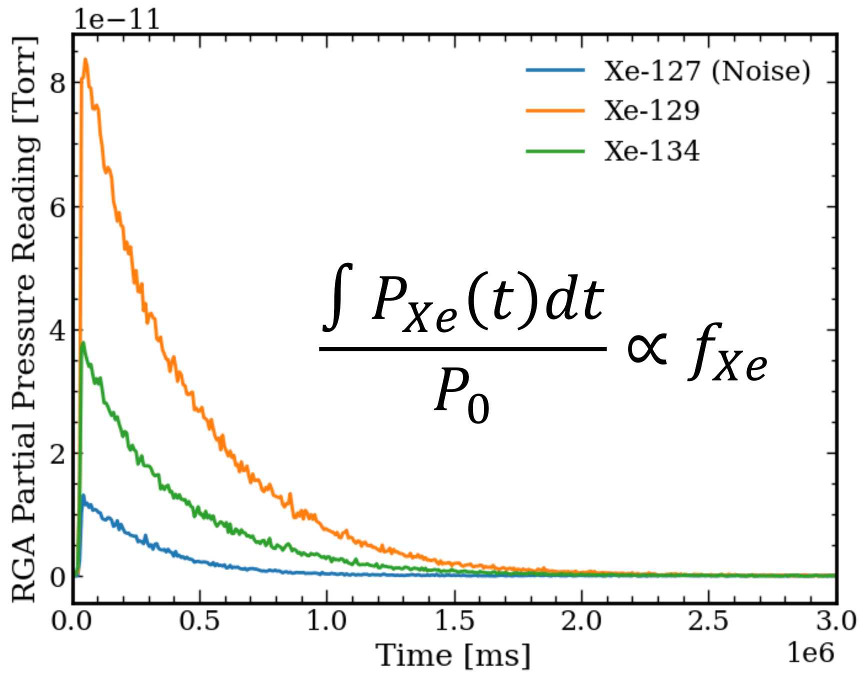
- Gas Xe concentration determines S2 response
- RGA operates in vacuum

Operates at $<10^{-4}$ Torr

Integrating Xe partial pressure effectively "counts" the xenon in the integration volume!

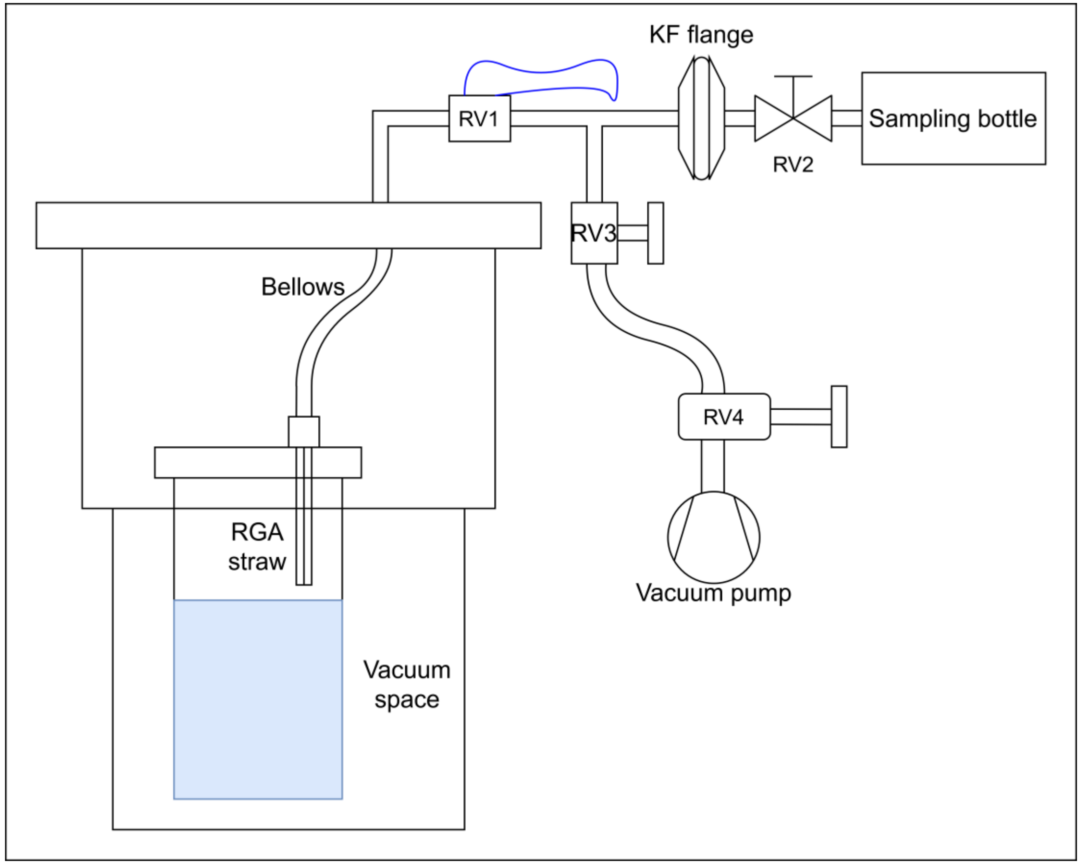
Gas Sampling Calibrations and Measurements





- Xe-127 is the noise background to be subtracted
- Fixed volume ➔ fixed calibration curve
- **Measured** 64±4 ppm of Xe in Ar gas at 4% Xe concentration in LAr!

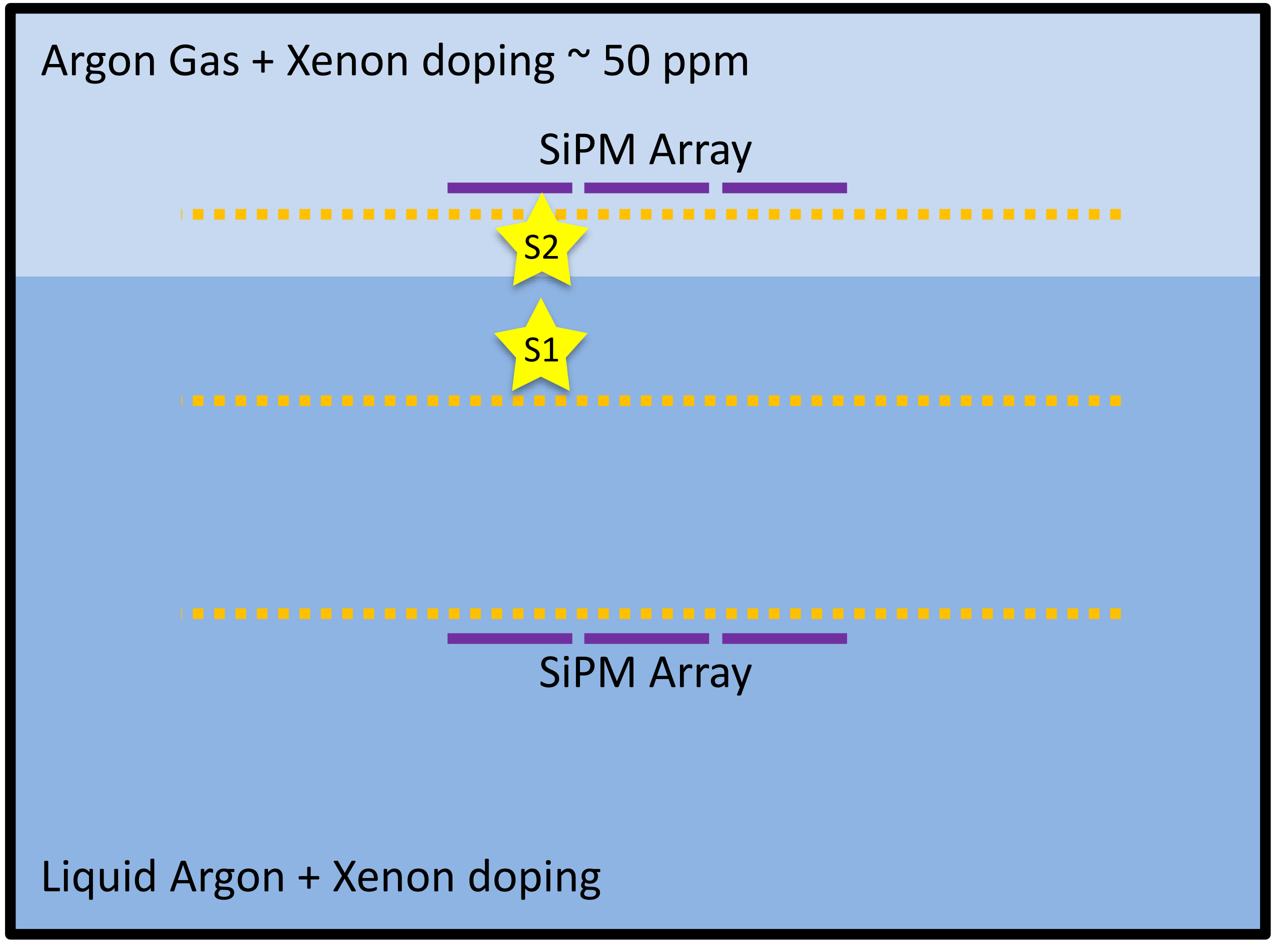
Gas Sampling During Operation



Liquid Xe concentration	Gas Xe concentration (measured)	Gas Xe concentration (predicted)
1%	14 ± 4 ppm	16 ppm
2%	34 ± 4 ppm	32 ppm
3%	57 ± 4 ppm	49 ppm
4%	65 ± 4 ppm	66 ppm

- Gas sampled via a straw right above the anode
- Samples the gas approximately near S2 production
- In practice, small ice build-up can affect the measurement

Two-Grid TPC



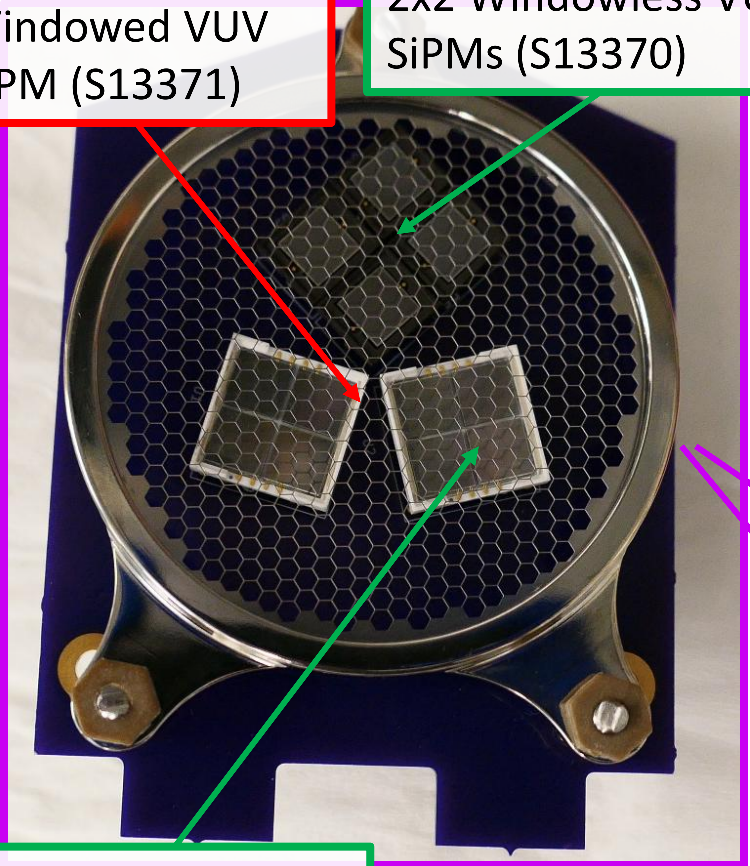
Detector Vessel

- Cathode is the only HV component
- No gate
- Strong extraction and drift field
- ~1 cm drift region, ~5 mm gas region

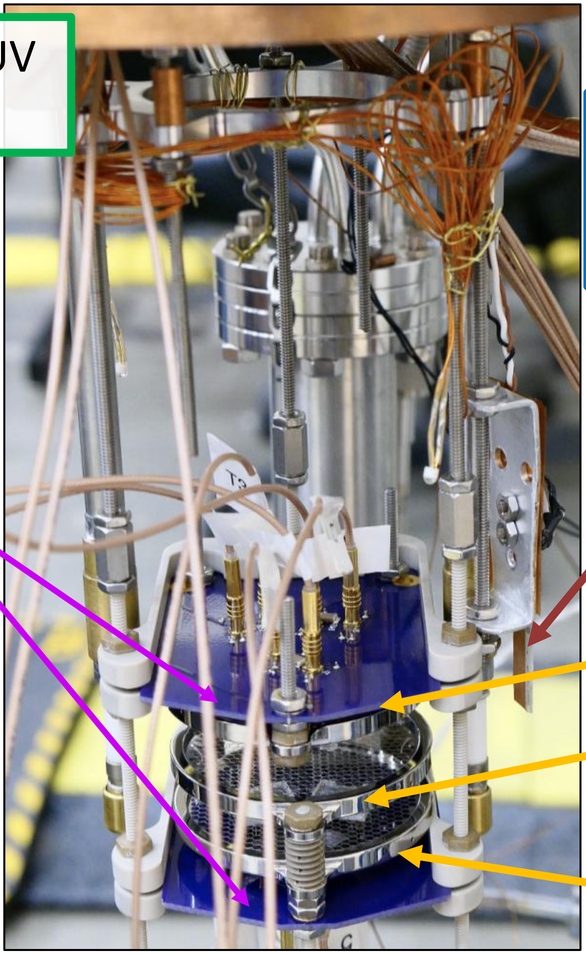
TPC Internals: Two Grid TPC Prototype

Windowed VUV SiPM (S13371)

2x2 Windowless VUV SiPMs (S13370)



Windowless VUV SiPM (S13371)



Front view

Not shown: RGA ”straw” and capacitor (for measuring Xe)

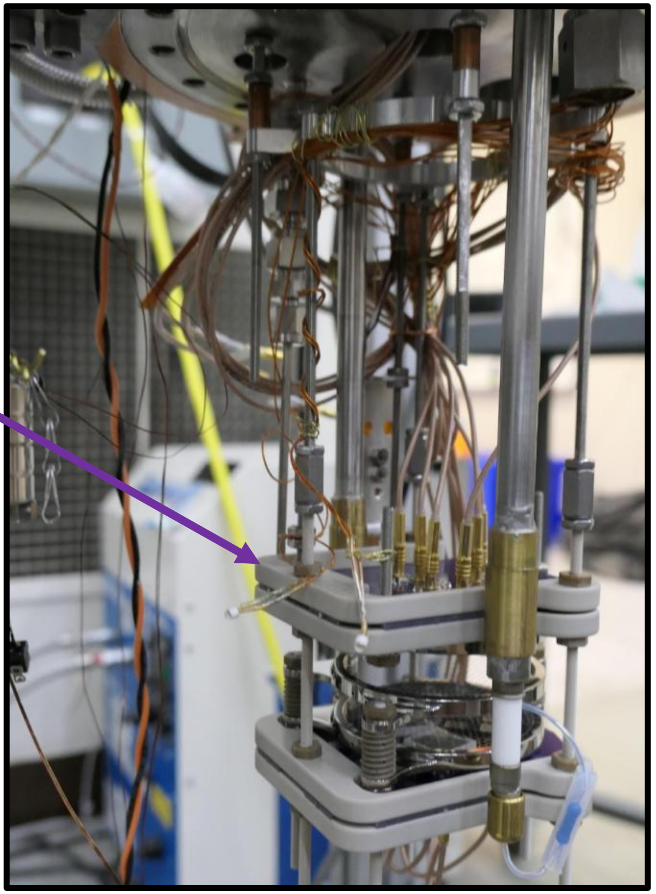
LEDs

Liquid Level meter

Anode (0 kV)

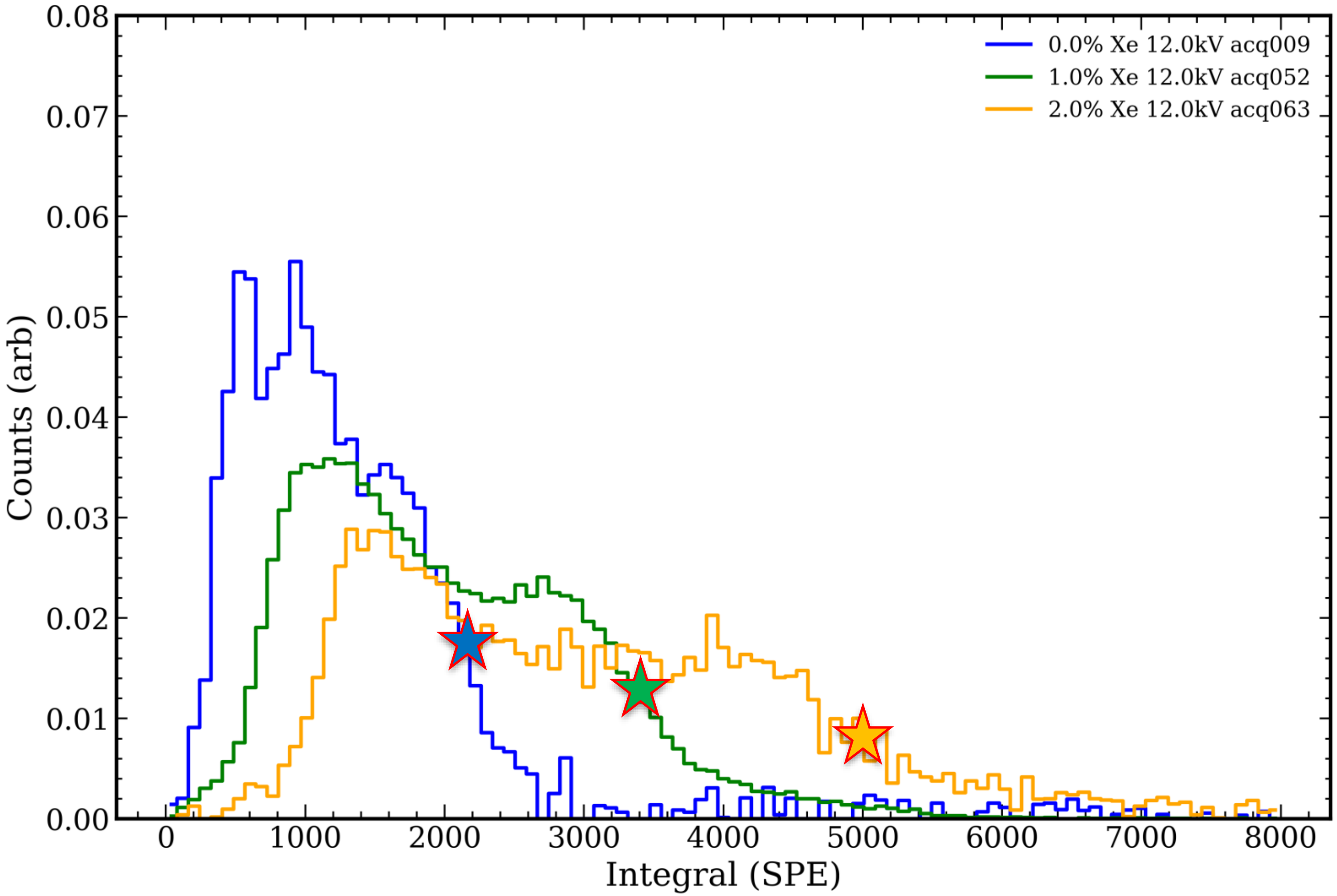
Cathode (10 kV – 14 kV (negative))

Shield (0kV)



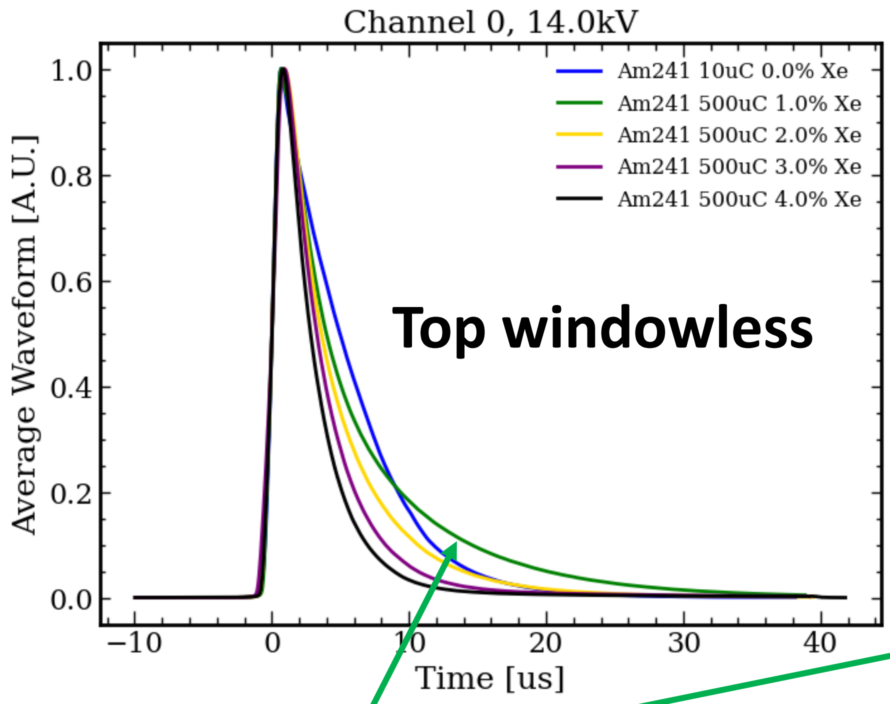
Back view

Effects of Doping: Total Light Production

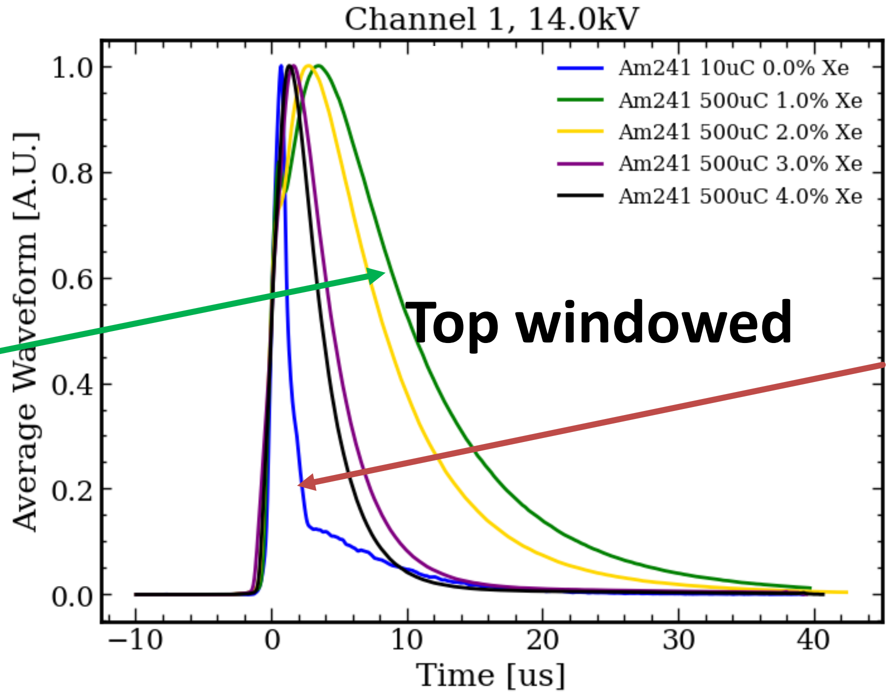


The Am-241 endpoint increases by a factor of >2 from pure LAr to 2% Xe

Effects of Doping: Pulse Shape



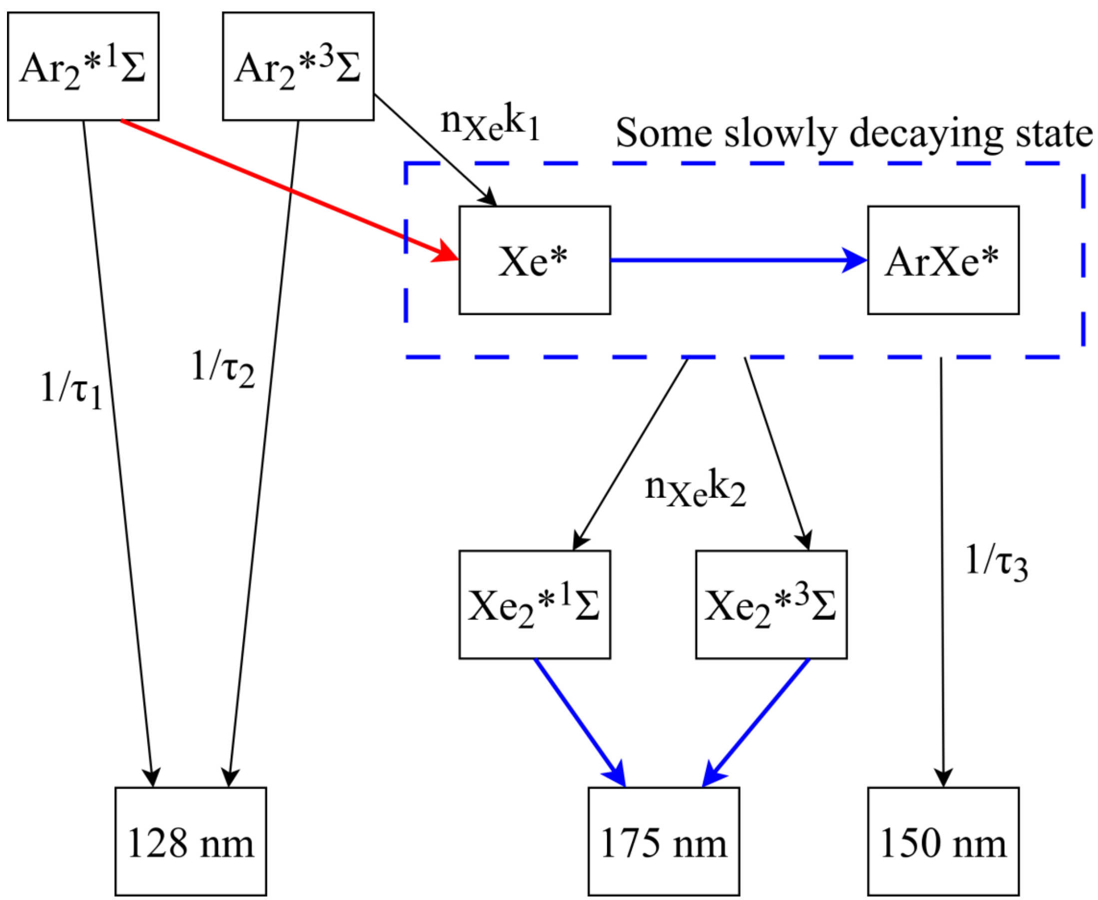
Average S2 waveform gets *broader* at 1% xenon-doping, then *narrower* at ≥2%



Windowed SiPM shows a *rounded hump* compared to the windowless SiPM

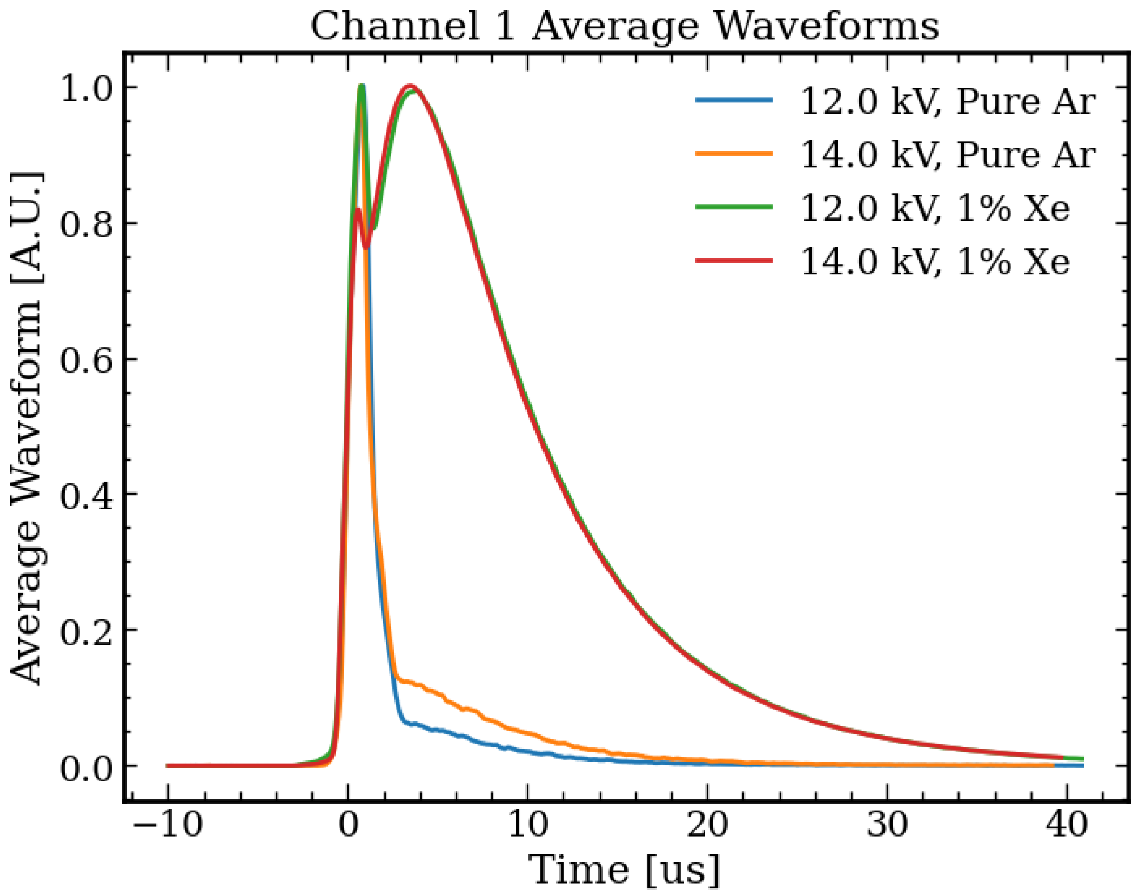
Only a sharp pulse in pure Ar (windowed SiPM cannot see Ar_2^* light)

Model of Electroluminescence Mechanism



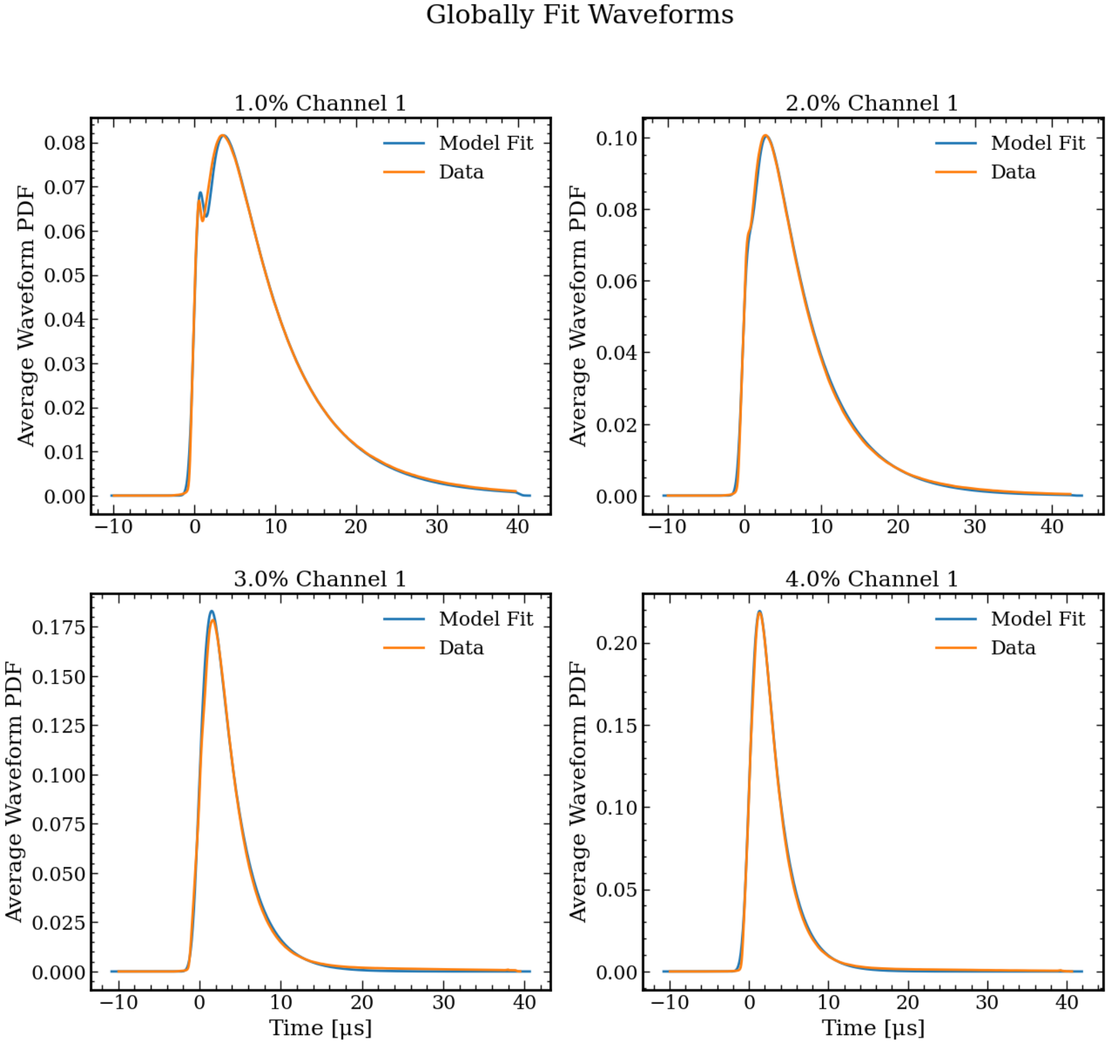
- Ar_2 triplet forms Xe* (slow process, microseconds)
- Unknown long-lived state
  - Either Xe* or ArXe*, literature is unclear
  - Can decay into 150 nm light
- Rates increasing with n_{Xe} narrows the S2 pulse
- **Hump is formed from the two step process:**
  $Ar_2 \rightarrow$ (Xe* or ArXe*) $\rightarrow Xe_2^*$

Extra Sources of S2 Light: A Sharp Rise



- Sharp rise in windowed SiPM is unexplained by the model
- Sharp rise is present *even in* pure Ar
    - Likely not VUV light
- Becomes relatively suppressed at higher voltages

Fitting of the S2 Pulse Shape

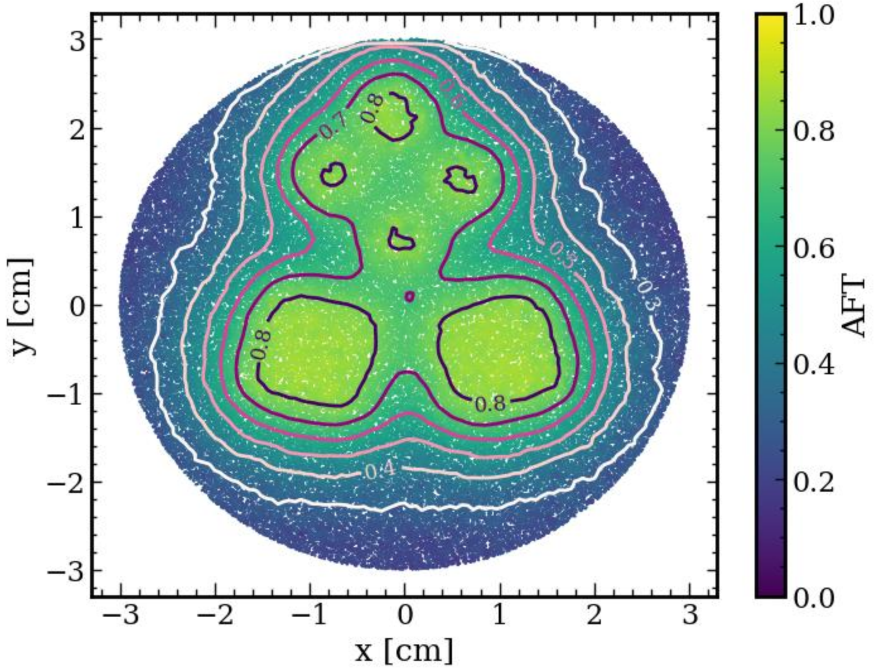


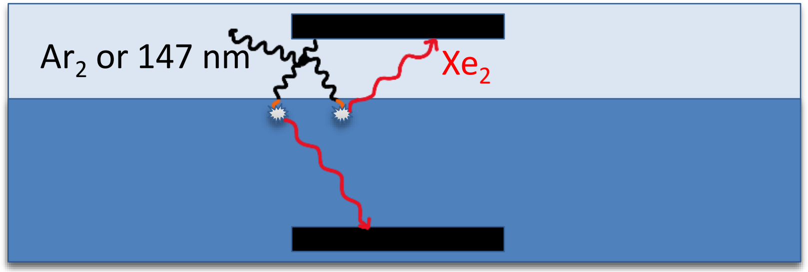
- Pulse shape:

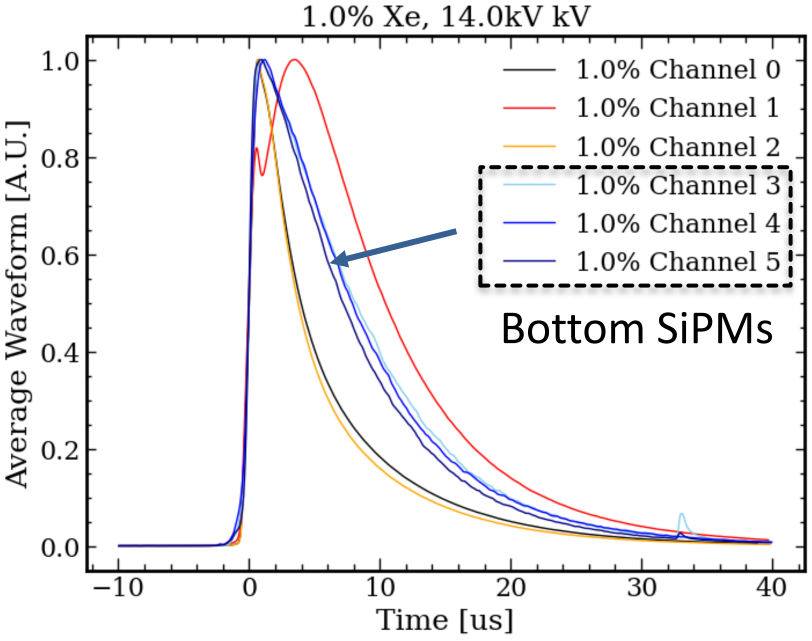
$$e^{-t(\frac{1}{\tau_3}+k_2 n_{Xe})} - e^{-t(\frac{1}{\tau_2}+k_1 n_{Xe})}$$

- Convolved with SE transit time and SPE shape
- Fitting the parameters for all four concentrations at once yields a reasonable fit
- Fits are for the windowed channel at 14 kV on the cathode

Extra Sources of S2 Light: Wavelength Shifting in the Liquid

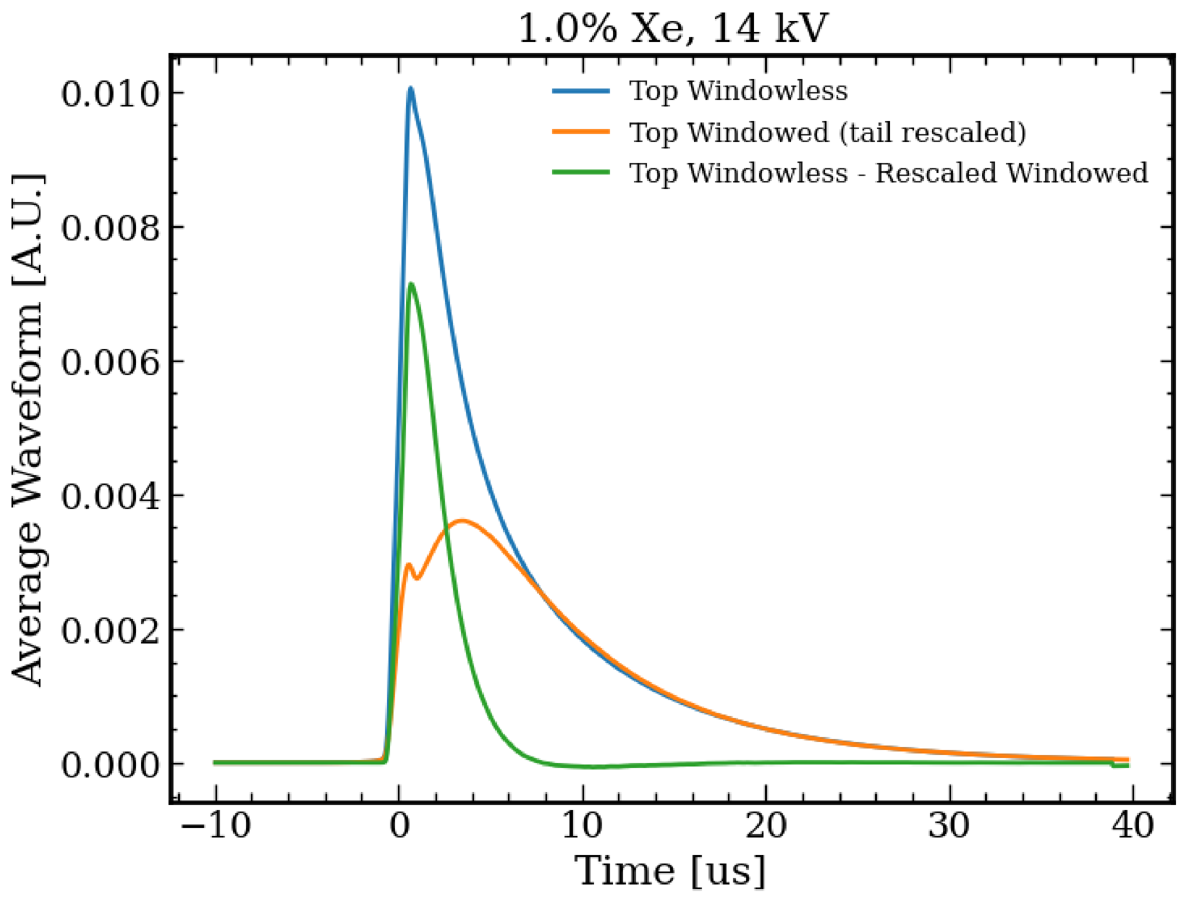






- Xe has absorptions near 128 nm *and* 147 nm
- Bottom channels:
  - Average waveform differs from *all* top SiPMs
  - Windowed sees comparable amount of light
  - **Likely see re-emitted 128 nm and 147 nm photons in Xe wavelength**
- Some re-emitted light may re-emit to the top SiPMs

Estimation of the Xe Component



- Xe_2 component is the slowest exponential
- At long times, the tails of the windowless and windowed waveforms should match
- We can:
  - Match amplitudes
  - Windowless/Windowed ≈ Fraction of light from Xe_2^* de-excitation
  - (only works at 1% Xe)

Cathode voltage [kV]	% of light from Xe_2^*
12	64
14	69

Conclusion

We are operating the world's first dual phase O(1%) xenon-doped argon two-grid TPC.

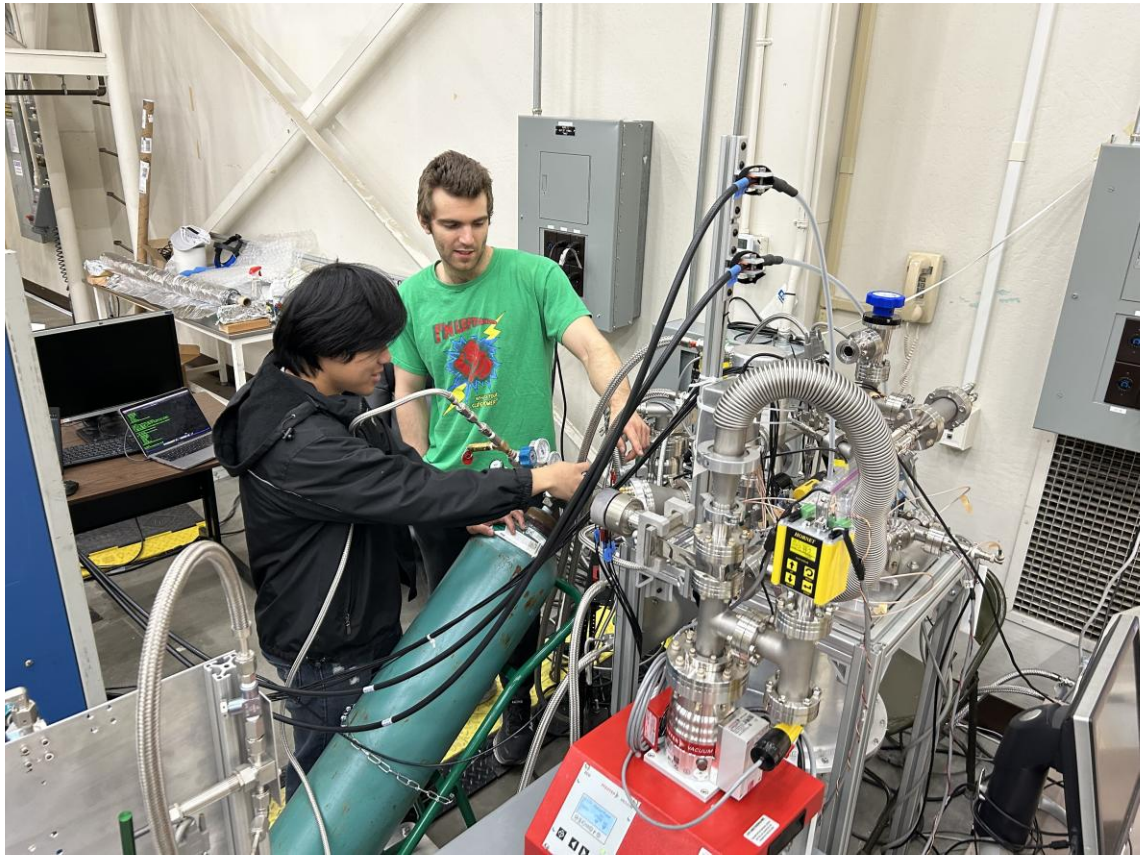
We see substantial S2 gain from xenon-doping .

S2 average waveform gets broader at 1%, then narrows for ≥2%.

S2 light production mechanism is being demystified.

Plan to upgrade CHILLAX with more SiPMs, full TPC, and reflector coming soon!

Thank you! Questions?



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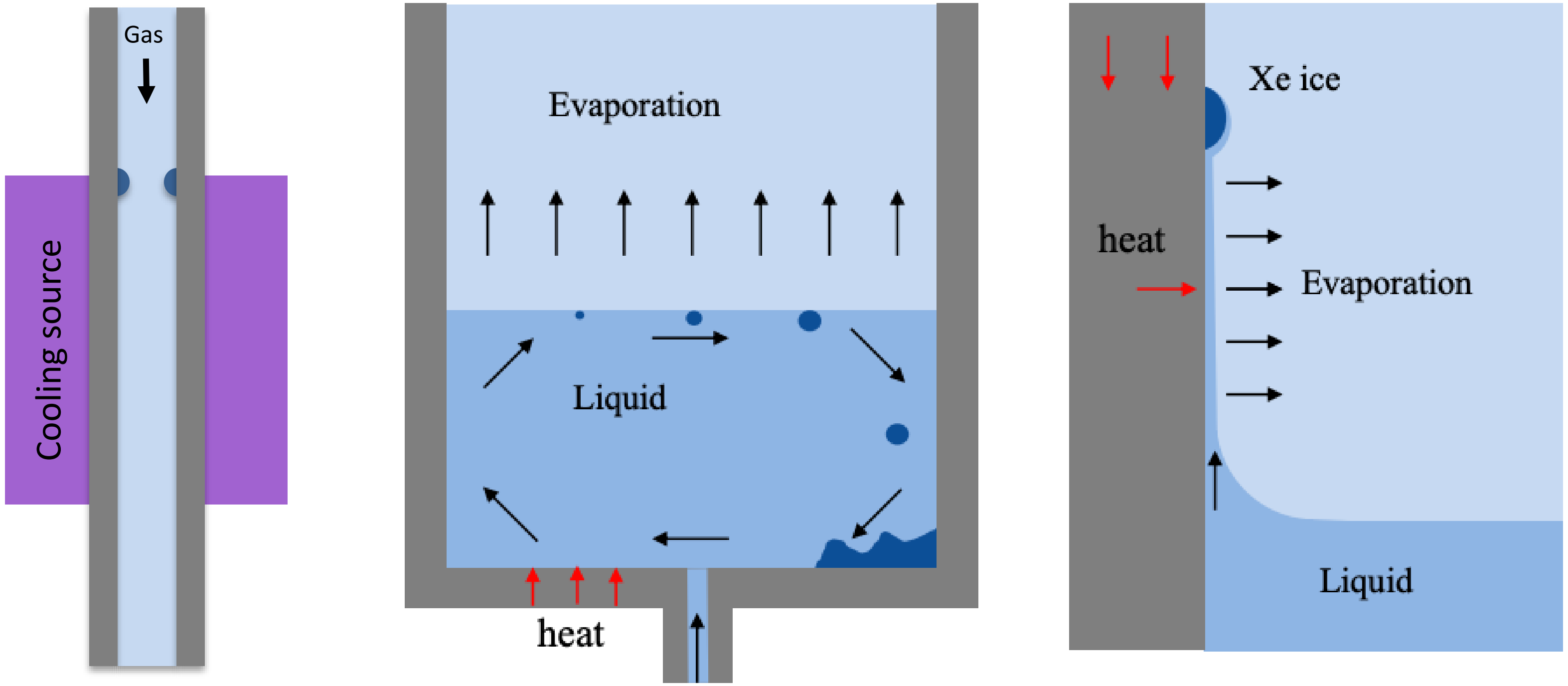
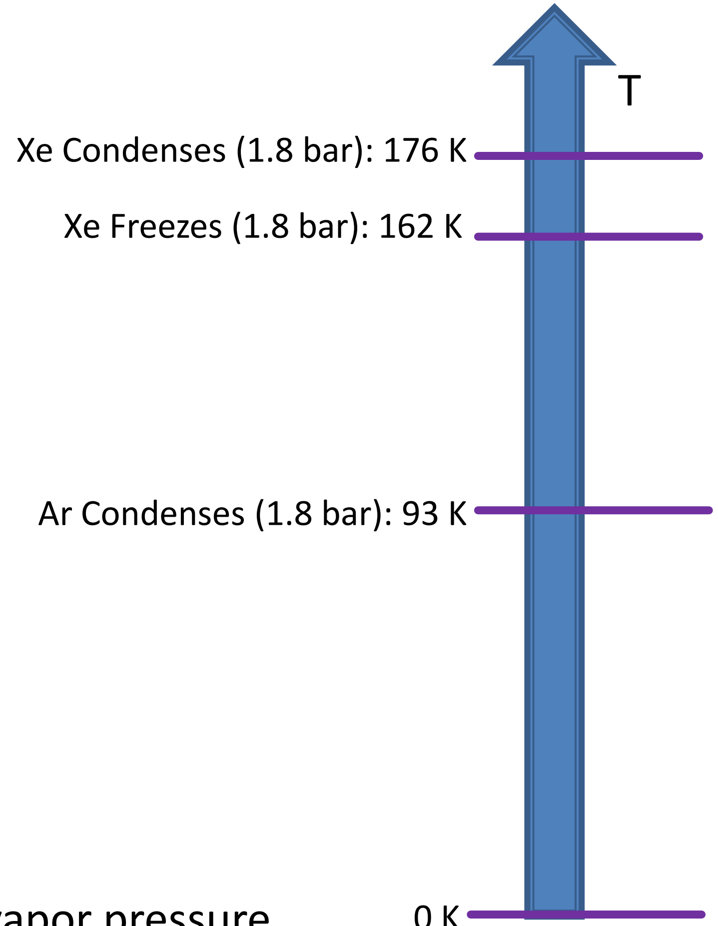
Backup Slides

Complications from Xenon-Doping

The large temperature discrepancy between xenon and argon boiling points are a major source of system instability

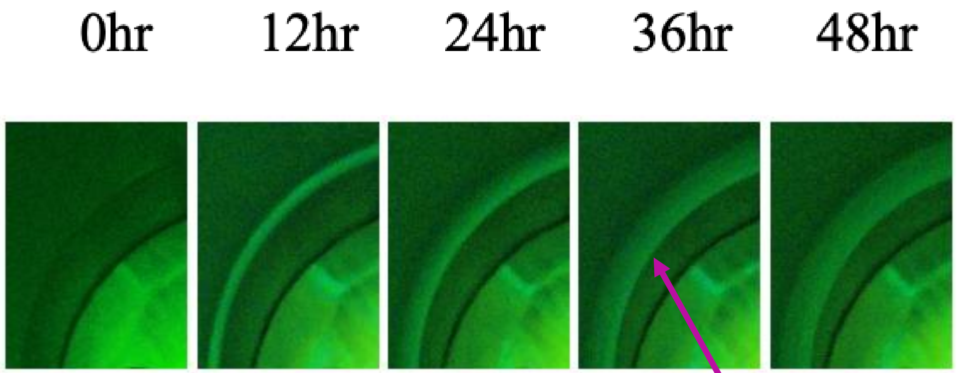




Left: Condensation of Xe-rich Ar gas causes Xe to freeze if Xe pressure exceeds saturation vapor pressure
Middle: Evaporation of liquid mixture causes Xe concentration to increase in the liquid
Right: Unintended evaporation of liquid isolated by surface tension can cause Xe ice to form

Demonstration of Xe-Ar Mixture Stability (Past Work)

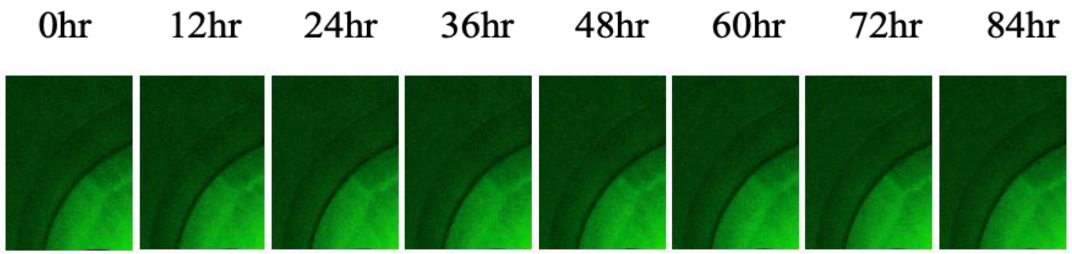
Unstable mixture:

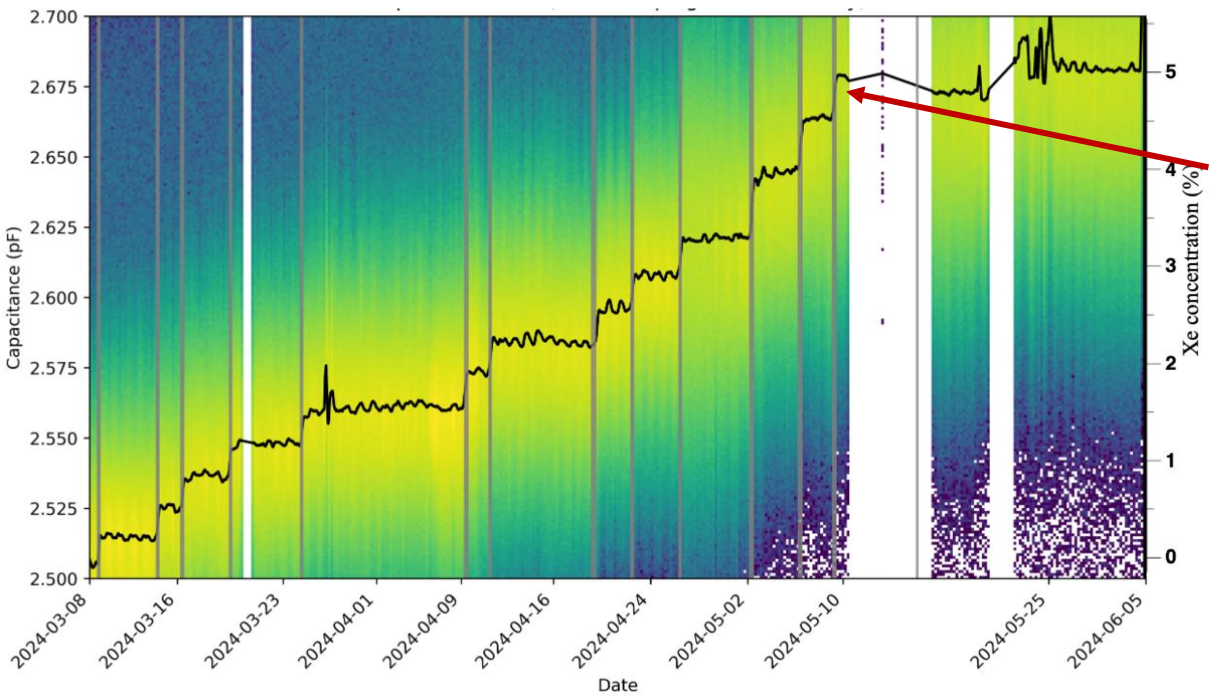


Cryostat view

Xe ice

Stable mixture:

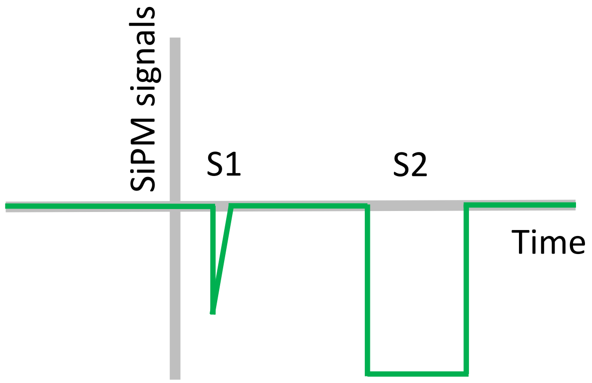




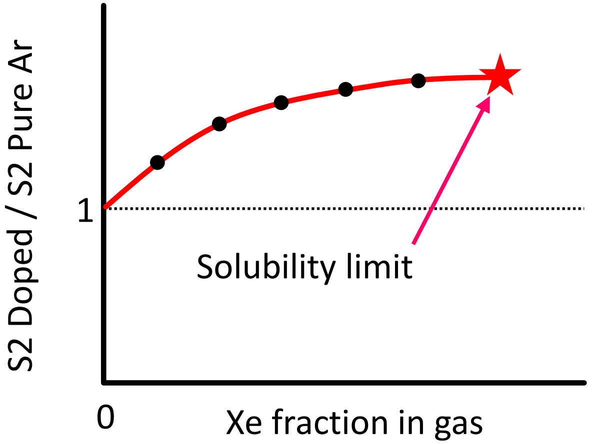
5.27% Xe!

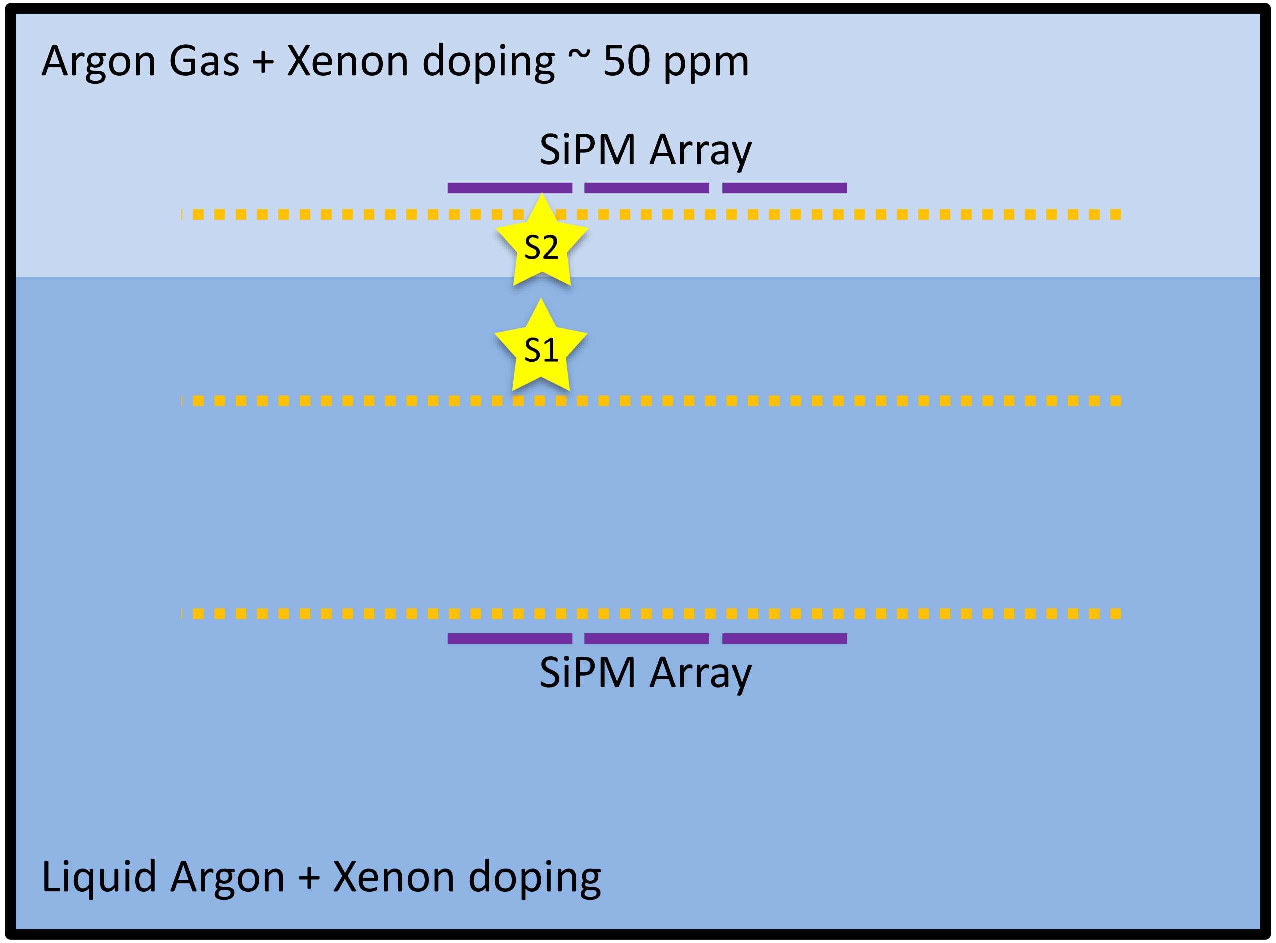
- Xenon Doping Periods in Gray
- Instabilities at the end of the run correspond to a failing heater

Xenon-Doped Argon S2 Experiment (2-grid TPC)



Anticipated data





Detector Vessel

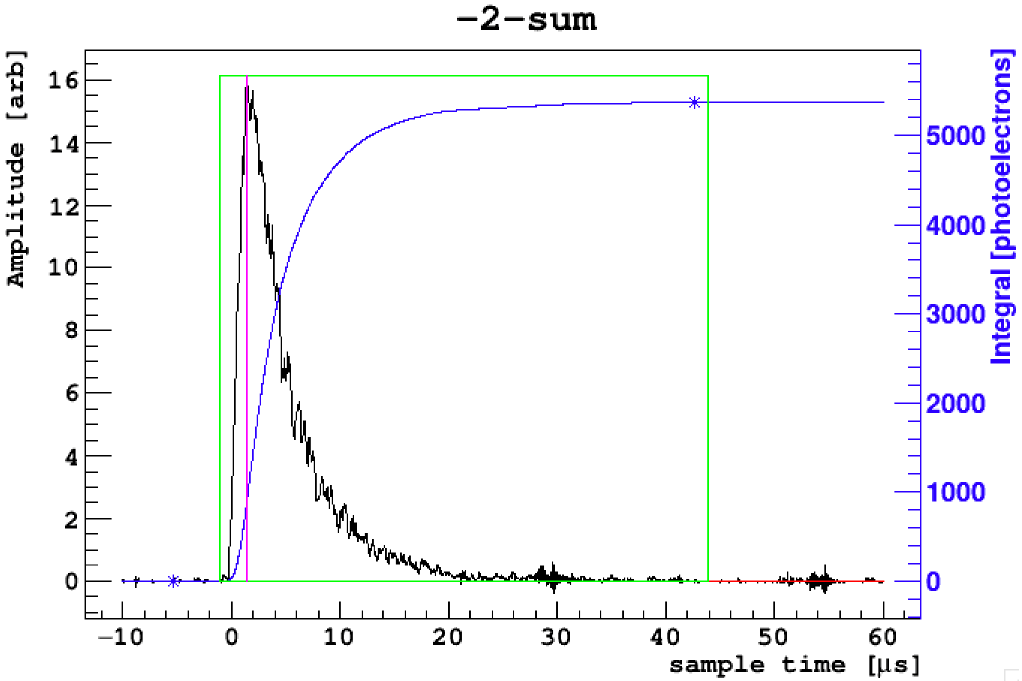
Example Waveforms

Windowless Channel (not trigger)

Windowless Channel (trigger)

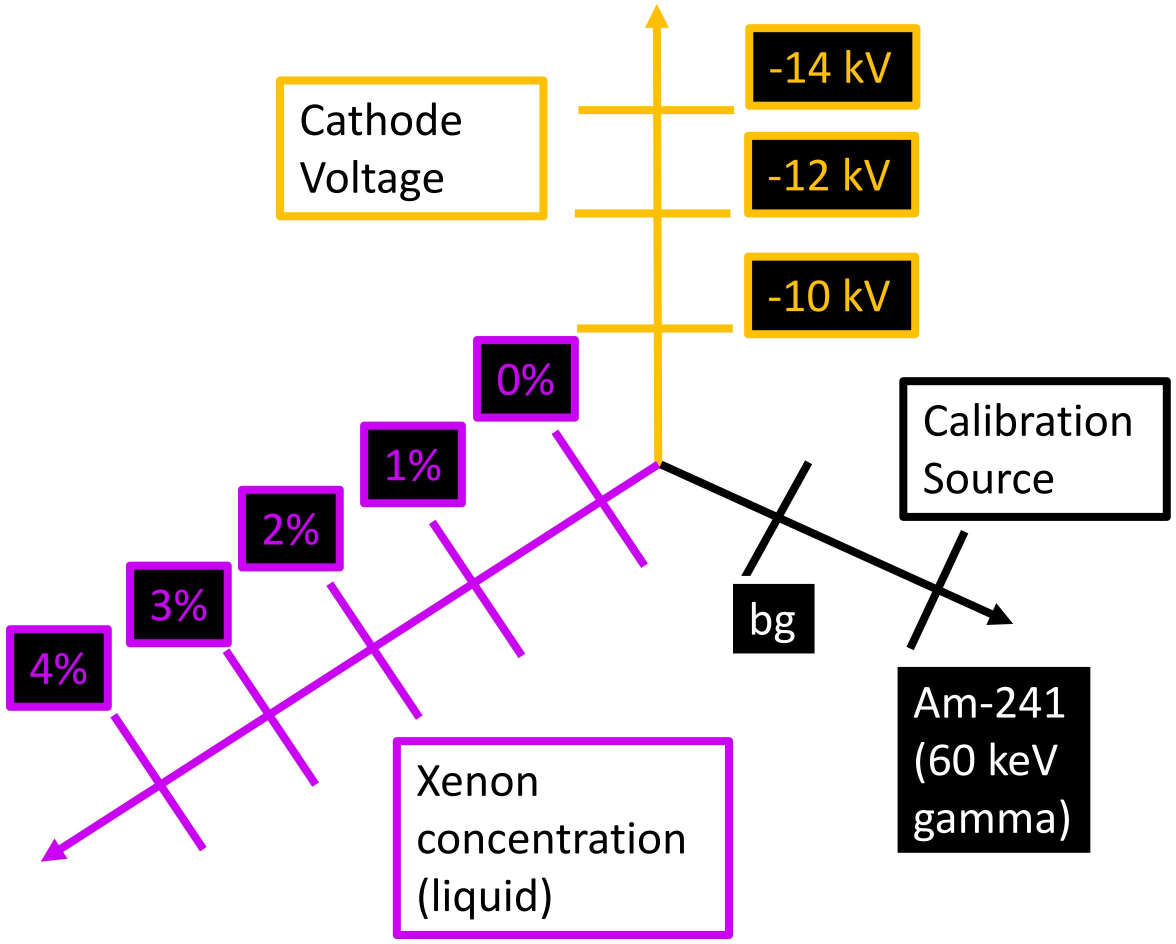
Windowed Channel (mostly opaque to Ar_2 and ArXe light)

S2s seen in top SiPM array on oscilloscope with Am-241 source (pure argon)



S2 acquired with Struck SIS3316 Struck Digitizer (2% xenon)

Data Taking Configurations



Cathode HV	E-Field (liquid)	E-Field (gas)	Reduced E-Field
-10 kV	5.28 kV/cm	7.92 kV/cm	4.62 Td
-12 kV	6.34 kV/cm	9.51 kV/cm	5.54 Td
-14 kV	7.40 kV/cm	11.09 kV/cm	6.47 Td

Xe Concentration (liquid)	Xe Concentration (gas, predicted)	Xe Concentration (gas, measured)
1%	16 ppm	14 ± 4 ppm
2%	32 ppm	34 ± 4 ppm
3%	49 ppm	57 ± 4 ppm
4%	66 ppm	65 ± 4 ppm

Chemistry of Xenon-Doped Argon

Fast e- + Ar → slow e- + Ar*

Threshold 11.8 eV

Fast e- + Xe → slow e- + Xe*

Threshold 8.4 eV

Example: Electrons inelastically colliding with xenon or argon

$Ar^* + Ar \rightarrow Ar_2$

$Ar^* + Xe \rightarrow ArXe^*$

$Xe^* + Xe \rightarrow Xe_2$

Argon and xenon form metastable excimers

$Ar_2 \rightarrow 2\,Ar + h\nu$ (128 nm, 1.6 us in liquid, 3.6 us in gas)

$ArXe \rightarrow Xe + Ar + h\nu$ (147 nm, (?) ns)

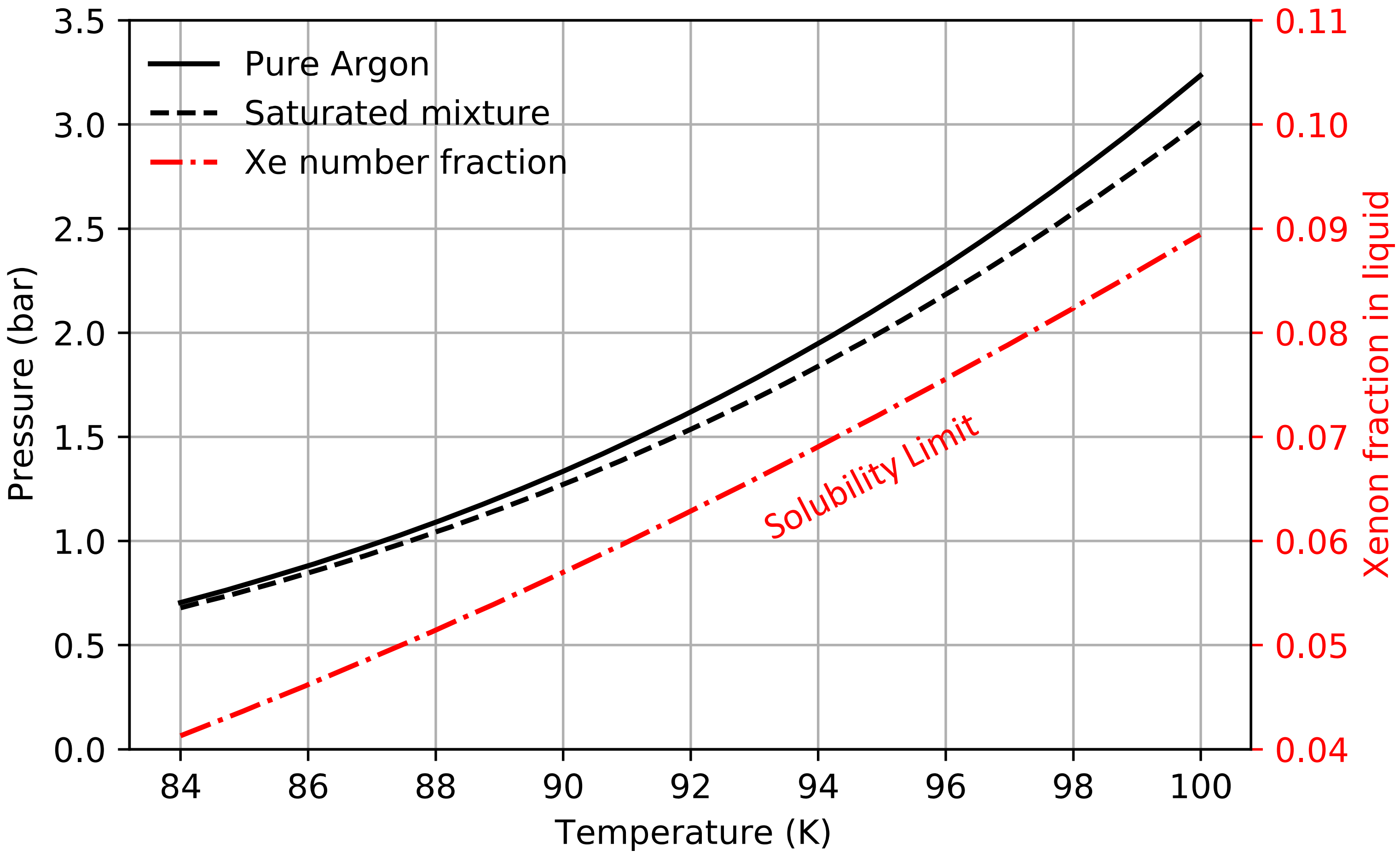
$Xe_2 \rightarrow 2\,Xe + h\nu$ (178 nm, 22 ns in liquid, 100 ns in gas)

Excimers decompose and release scintillation light

Thermodynamics of Xenon-Doped Argon

Xenon-argon miscibility is highly dependent on temperature

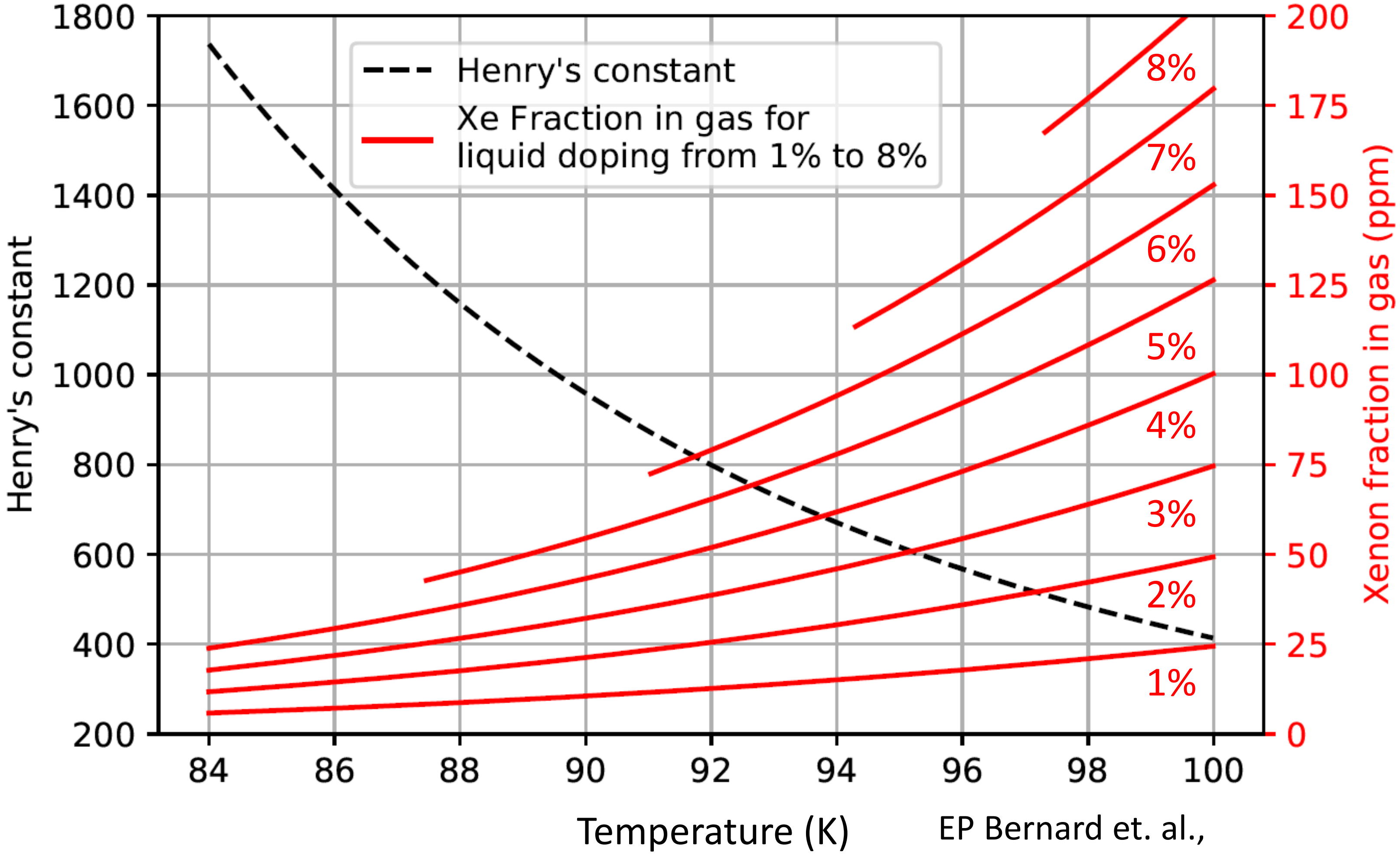
Xenon-doping past the solubility limit results in unwanted xenon solid formation



Thermodynamics of Xenon-Doped Argon

Recall: S2 light shifts from Ar_2 at O(10 ppm) level

You need to dope percent level Xe in LAr to get 10s of ppm of Xe in GAr!



EP Bernard et. al., Phys. Rev. C **108**, 045503

Capacitive Technique to Measure Xenon Concentration in Argon

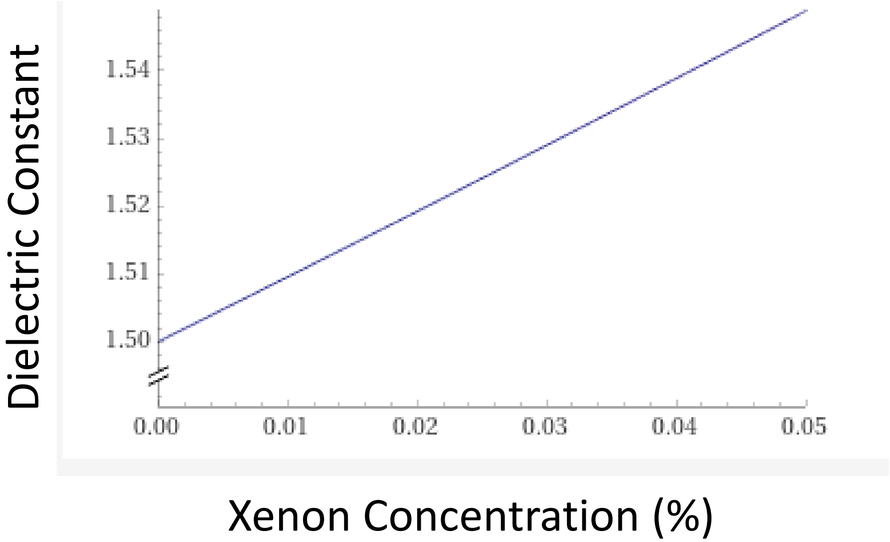
The dielectric constant of xenon-doped argon can be determined by the Clausius-Mossotti equation:

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \sum_{i=1}^{2} \frac{n_i \alpha_i}{3\varepsilon_0}$$

n_i: number density of molecule (or atom) type i

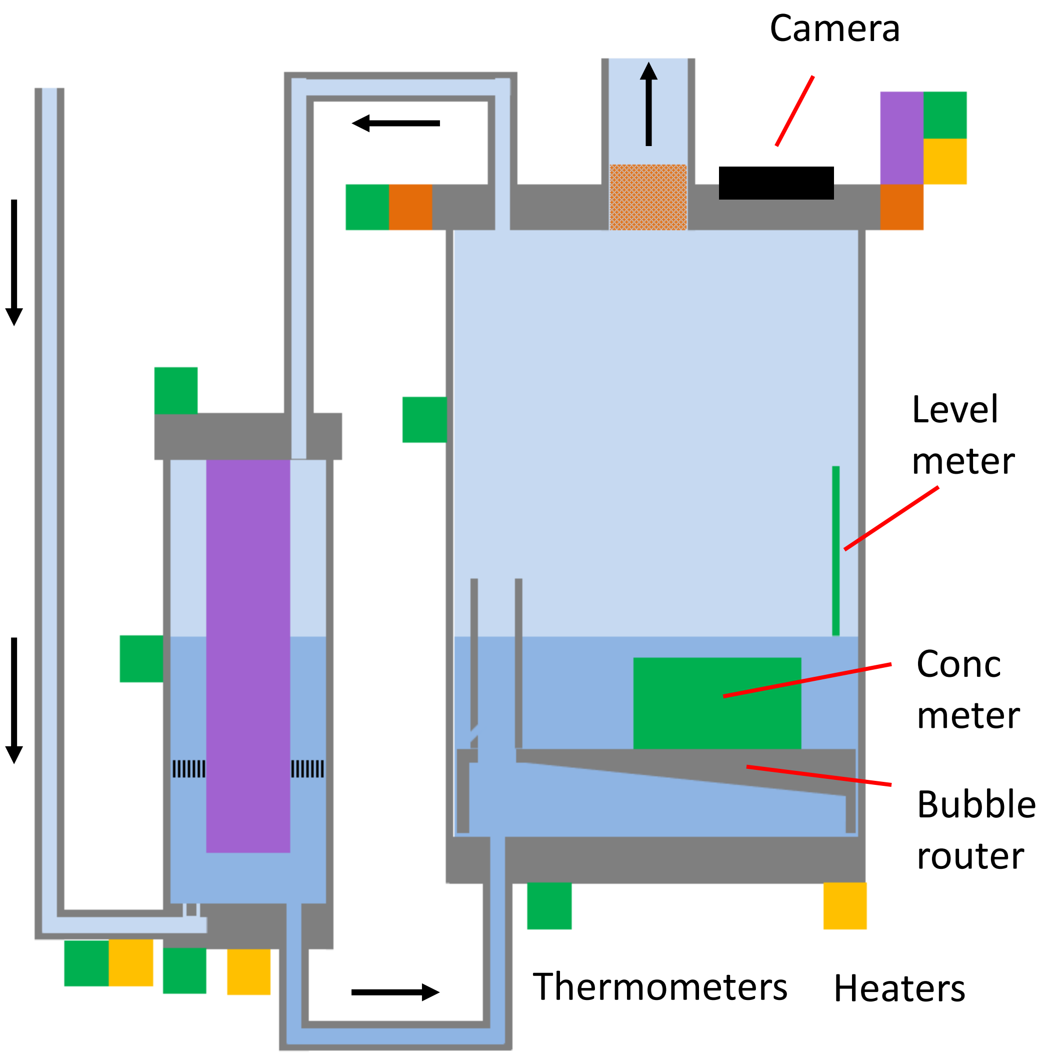
α_i: atomic polarizability of molecule type i

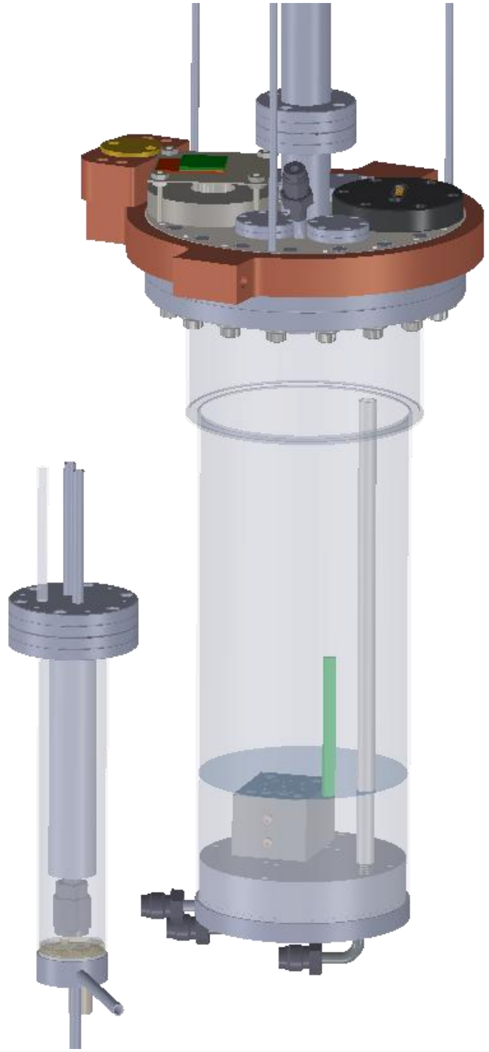
One can derive a nearly linear dependence of ε_r on F_{Xe}:



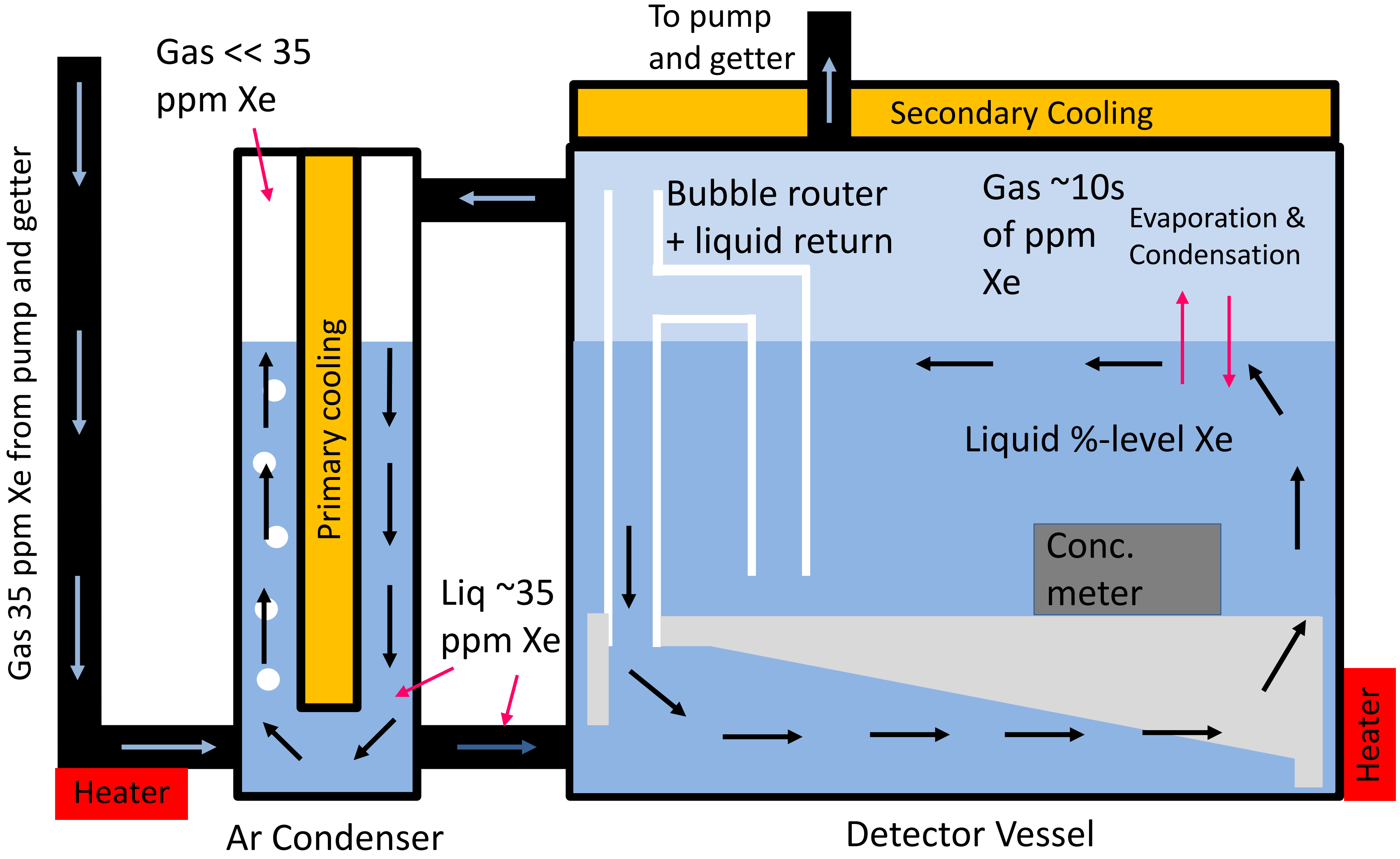
Then the capacitance of a capacitor with a xenon-doped argon dielectric medium is linearly dependent on the xenon concentration

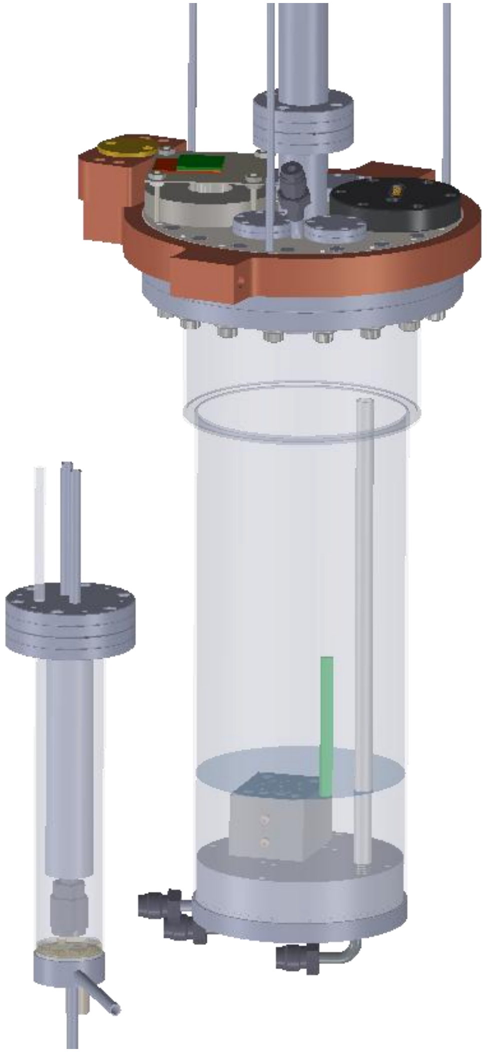
Circulation Design





Circulation Design

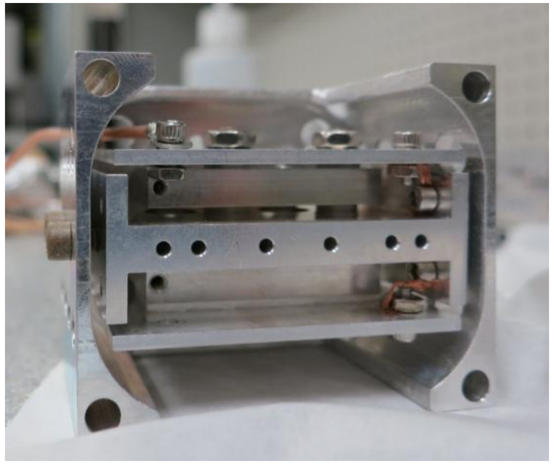




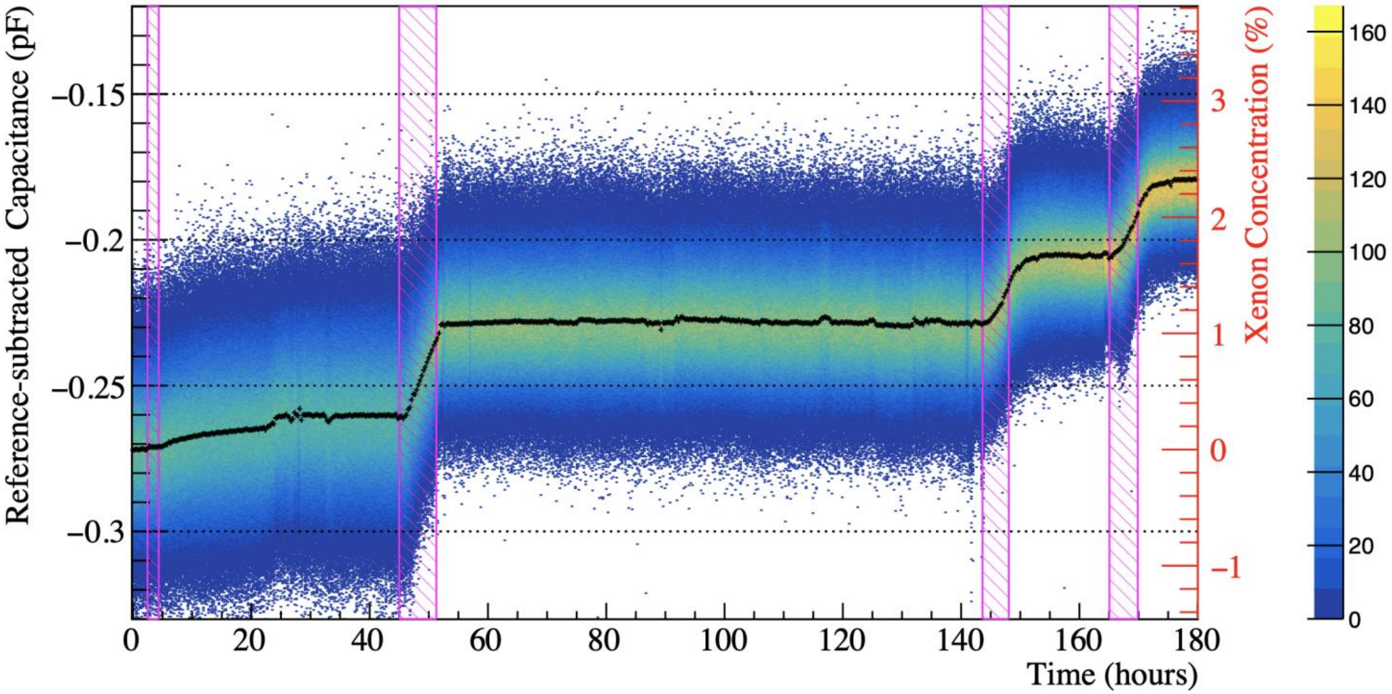
Capacitance and Xenon Concentration in Response to Doping

The CHILLAX capacitor tracks xenon concentration throughout the doping process with 0.05% precision

The capacitor is sensitive to variations in doping conditions (fast vs slow introduction of xenon)



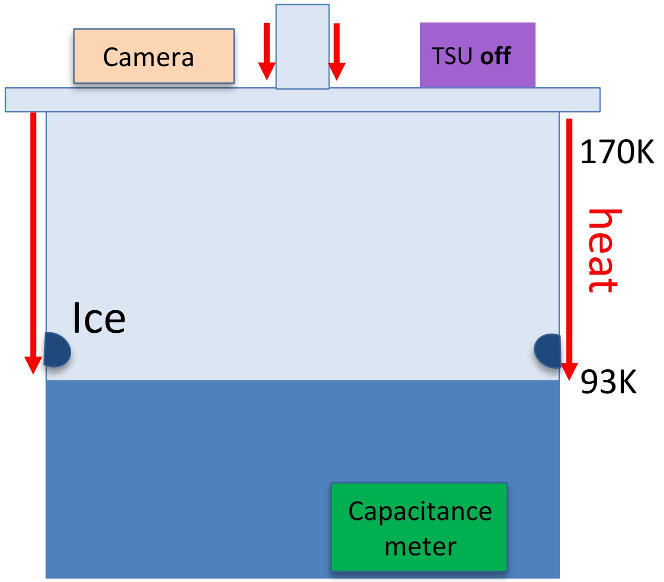
Drifts in capacitance should be attributed to changes in xenon concentration or temperature

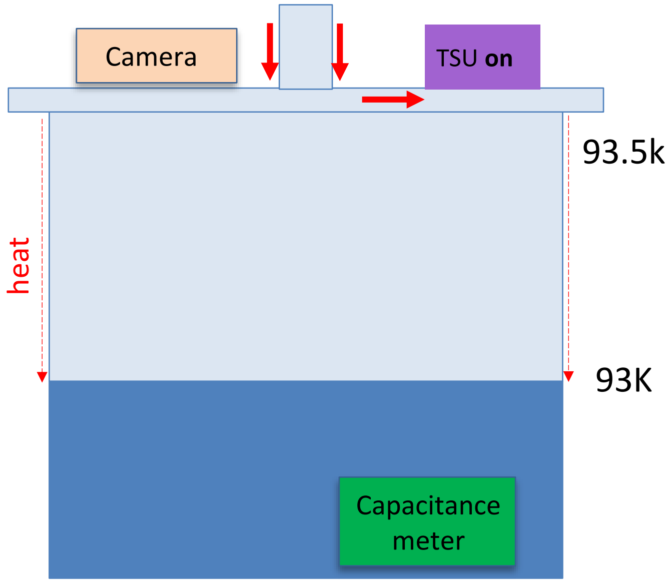


Capacitance and xenon concentration in CHILLAX over time, with doping stages highlighted in pink

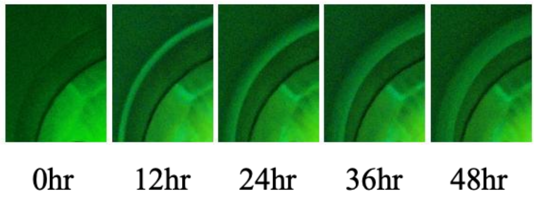
Stability Tests with Controlled vs Uncontrolled Detector Temperature Gradient

Controlling thermal profile with thermosiphon at top of detector greatly enhances xenon stability in detector volume

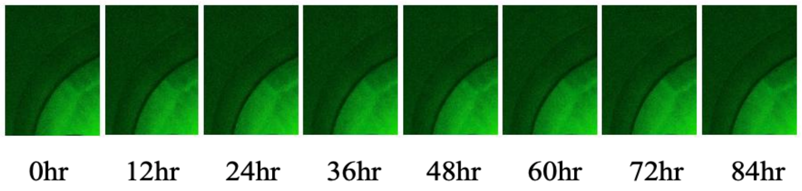




Change in xenon concentration results in change in signal characteristics. Detrimental for any detector's performance!

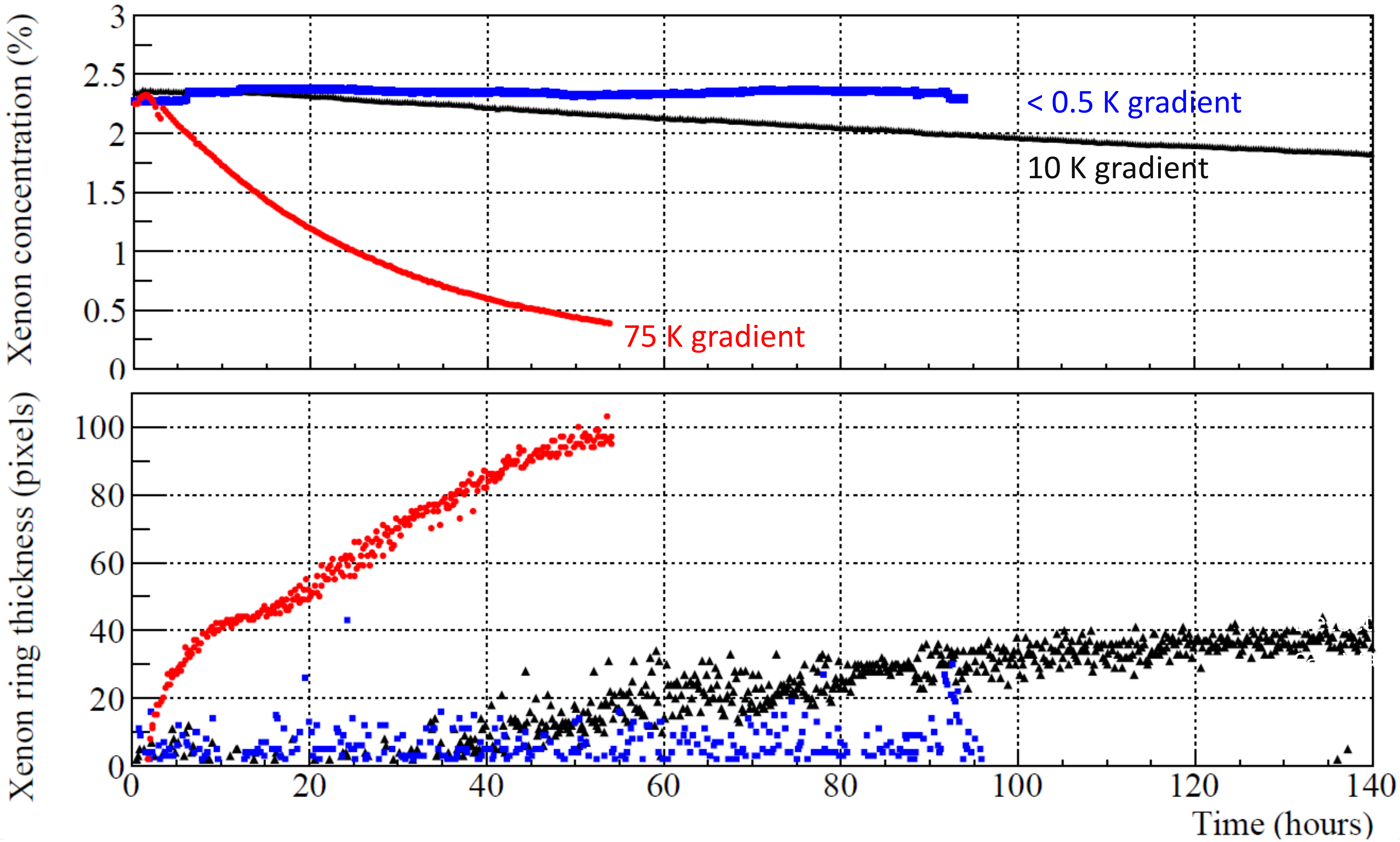


A 95 K temperature gradient results in rapid ice buildup

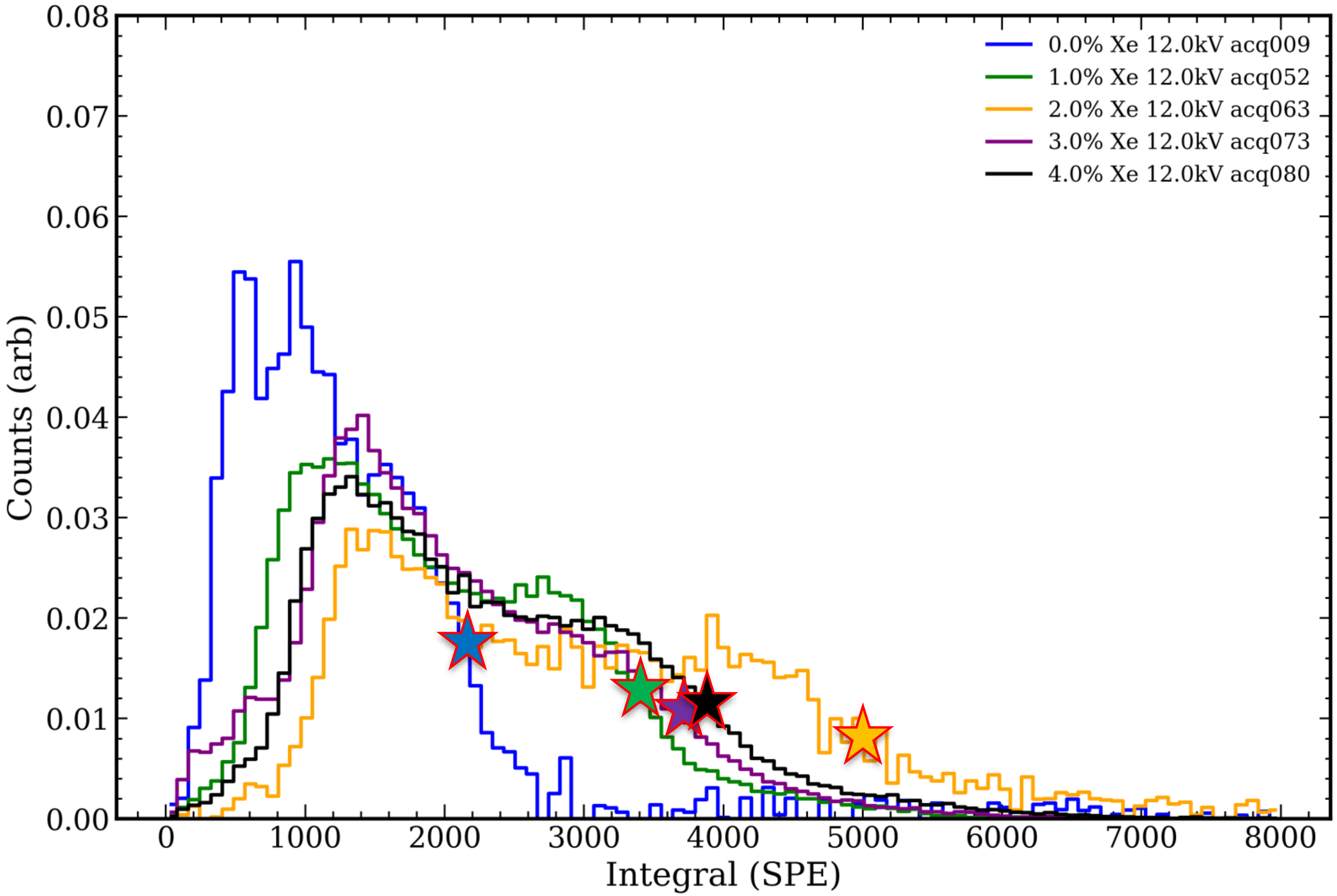


Maintaining a 0.5 K temperature gradient prevents ice buildup for at least 3.5 days

Capacitive and Pixel Measurements of Xenon Stability Tests

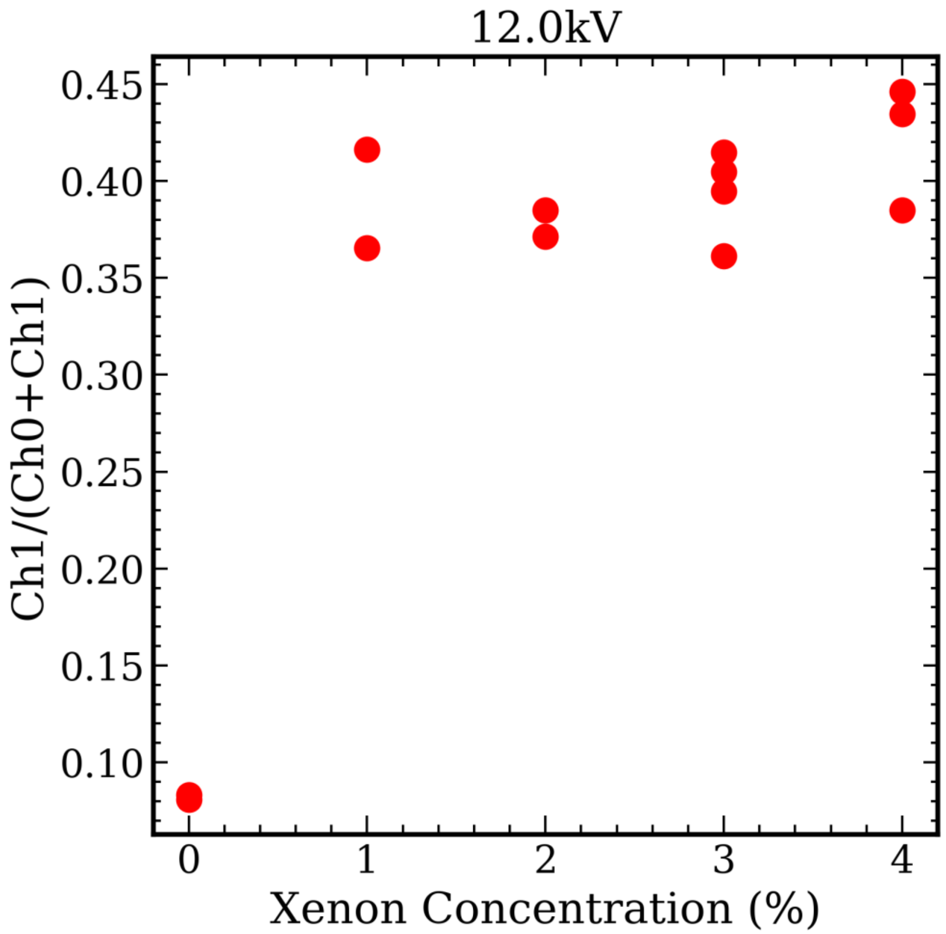


Effects of Doping: Total Light Production



The Am-241 endpoint decreases modestly past 2% (under investigation)

Light Ratio Between Windowed and Windowless SiPM



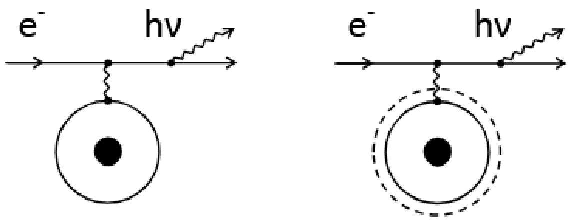
Ch0: **Windowless** S13371 SiPM (Top Array)
Ch1: **Windowed** S13371 SiPM (Top Array)

Fraction of light ratio seen in windowed SiPM plateaus at >1% xenon concentration.

Channel 1 (Windowed SiPM) sees nearly as much light as Channel 0 (Windowless SiPM) by 1%

Fused silica window still blocks some Xe_2 light.

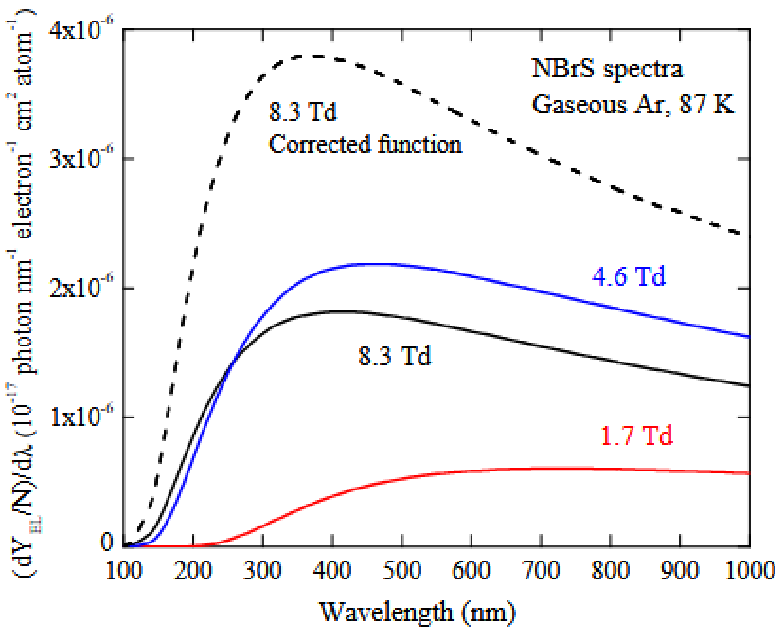
A Potential Explanation in Neutral Bremsstrahlung

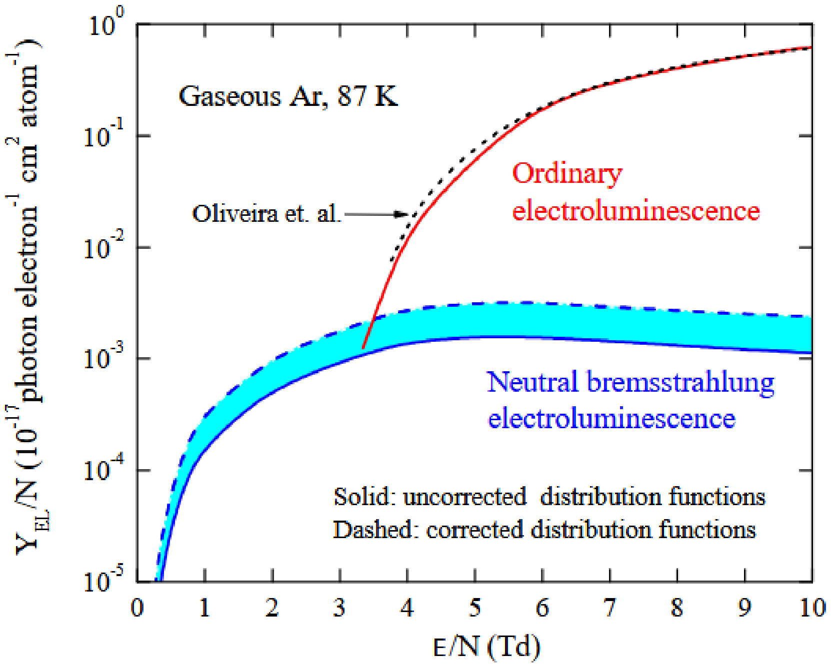


Neutral bremsstrahlung in elastic scattering

Neutral bremsstrahlung in inelastic scattering

Figures from Buzulutskov et. al. (https://arxiv.org/pdf/1803.05329)





- Light release from elastic scatters
- Broad spectrum (windowed SiPM would see)
- Fast (no de-excitation)
- Doesn't increase with electric field